Defence Research and Development Canada | Recherche et développement pour la défense Canada

DEFENCE | DÉFENSE

Developing a framework for estimating the costs/benefits of teamwork in C2

Richard Breton
Daniel Lafond
DRDC Valcartier

Sébastien Tremblay
Robert Rousseau
C3 S.E.N.C.

Defence R&D Canada – Valcartier
Technical Report
DRDC Valcartier TR 2010-225
September 2011

Canada

Developing a framework for estimating the costs/benefits of teamwork in C2

Richard Breton
Daniel Lafond
DRDC Valcartier

Sébastien Tremblay
Robert Rousseau
C3 S.E.N.C.

Defence R&D Canada – Valcartier

Technical Report
DRDC Valcartier TR 2010-225
September 2011

Principal Author

Original signed by Richard Breton

Richard Breton

Defence Scientist / C2DSS

Approved by

Original signed by Patrick Maupin

Patrick Maupin

Section head / C2DSS

Approved for release by

Original signed by Christian Carrier

Christian Carrier

Chief Scientist

This report presents the result of the contract W7701-6-2709 executed under the WBEs Team Modelling using T-OODA (WBE: 16ki05, fiscal year: 2006-07; 2007-08) and Team Modelling (WBE: 16re01, fiscal year: 2008-09) on Modelling Team Performance ARP.

In conducting the research described in this report, the investigators adhered to the policies and procedures set out in the Tri-Council Policy Statement: Ethical conduct for research involving humans, National Council on Ethics in Human Research, Ottawa, 1998 as issued jointly by the Canadian Institutes of Health Research, the Natural Sciences and Engineering Research Council of Canada and the Social Sciences and Humanities Research Council of Canada.

Abstract

This document presents a modeling framework for estimating the cost and benefits of various team structures in Command and Control (C2). The proposed strategy combines task analysis and data-driven modeling as a means to deal with effective team design in military C2. A hierarchical task analysis (HTA) identified the set of subtasks associated with different components of a simulated C2 task. For each team structure considered, we performed a task-to-agent mapping based on the HTA results in order to identify interpersonal task dependencies and identify the activities associated with each agent (taskwork, teamwork and interaction with tools). A mathematical model is then developed to quantify the impact of each element of that mapping on individual workload. Furthermore, the model specifies the effects of workload on team performance as a function of interpersonal dependencies. The calibration of the model is based on an empirical study that tests two team structures. We then describe a tool based on this model and test its potential to estimate the effectiveness of other team structures in order to identify the optimal team design for the simulated C2 task. Finally, future work for expanding this team design tool to different C2 domains is discussed.

Résumé

Ce document présente un cadre théorique de modélisation permettant l'estimation des coûts et bénéfices de différentes structures d'équipe en Commandement et Contrôle (C2). La stratégie utilisée combine une analyse de tâche à une modélisation basée sur les données afin d'influencer le développement et la formation d'équipes pour des situations de C2 militaire. Une analyse hiérarchique des tâches a contribué à l'identification d'un ensemble de sous-tâches associées aux différentes composantes d'une tâche de C2 simulée. Pour chaque structure d'équipe, une association tâche-à-agent basée sur les résultats de l'analyse hiérarchique est effectuée afin d'identifier les dépendances interpersonnelles dans l'exécution des différentes tâches et les activités pour chaque agent relié aux tâches à exécuter, au fait de faire partie d'une équipe et au fait d'interagir avec des outils. Un modèle mathématique est alors développé pour quantifier l'impact de chacun de ces éléments sur la charge de travail de chaque agent. De plus, le modèle spécifie les effets de la charge de travail sur la performance de l'équipe en fonction des dépendances interpersonnelles. L'étalonnage du modèle est basé sur une étude empirique qui mesure la performance de deux équipes adoptant des structures organisationnelles différentes. Le modèle mathématique étalonné est alors utilisé pour tester son potentiel à évaluer l'efficacité d'autres structures d'équipe afin d'identifier la structure d'équipe optimale pour l'exécution de la tâche simulée de C2. Finalement, une discussion concernant les travaux futurs nécessaires à l'expansion de cet outil de design d'équipe aux différents domaines de C2 est présentée.

This page intentionally left blank.

Executive summary

Developing a framework for estimating the costs/benefits of teamwork in C2:

Richard Breton; Daniel Lafond; Sébastien Tremblay; Robert Rousseau; DRDC Valcartier TR 2010-225; Defence R&D Canada – Valcartier; September 2011.

Introduction: This document presents a modeling framework for estimating the cost and benefits of various team structures in Command and Control (C2). The proposed strategy combines task analysis and data-driven modeling as a means to deal with effective team design in military C2.

Results: A hierarchical task analysis (HTA) identified the set of subtasks associated with different components of a simulated C2 task. A task-to-agent mapping based on the HTA results identified interpersonal task dependencies and the activities associated with each agent (taskwork, teamwork and interaction with tools) for each team structure considered. A mathematical model, calibrated from an empirical study involving two team structures, quantified the impact of each element of that mapping on individual workload. Furthermore, the model specified the effects of workload on team performance as a function of interpersonal dependencies.

One major impact of this project was the demonstration of the relationship between key determinants of teamwork and team effectiveness that varied as a function of team structure. This demonstration came from the comparison of the coefficients found in two multiple regression models (for multifunctional and functional teams) relating team performance to a number of predictors of team effectiveness.

Also, key similarities and differences were observed, suggesting that some aspects of team functioning can markedly change as a function of team structure. The findings presented in this report suggested that teamwork requirements and the importance of various team factors in general may vary as a function of team structure. Obviously, communication and coordination are key components of teamwork, but their relative importance is affected by the manner in which the team is configured. For instance, results showed that communication was positively correlated with team performance in functional teams, but negatively correlated in multi-functional ones.

Finally, the mathematical model displayed an impressive capacity to replicate the results observed from the 20 three-person teams. From this model, it was possible to predict the performance of four other fictional teams.

Significance: Teamwork is often essential in complex and dynamic environments such as C2. In the domains of military operations and homeland security, there is a growing interest in team research, with the intention to improve efficacy through the use of networking. There are important issues with regards to inter-team operability and intra-team optimization of performance. This project provided interesting findings in regard to these C2 issues.

First, since different C2 team structures may rely upon different team processes, it would seem inadequate for future research to employ a general model of team performance that uses a fixed set of standard team processes as predictor variables. The role of these processes is not the same

from one team structure to another, and so such processes are an insufficient way to predict the performance of different team structures.

Second, this project defined the level of individual workload as a key predictor of team performance. The correlation between the level of workload perceived by the participants and the results from the model was astonishing. This remarkable result suggested that the workload metric based on the task-to-agent mapping represents accurately the actual workload of individuals.

Future plans: The possibility to use such models in order to identify the optimal type of team structure and the optimal number of team members is promising. To make it possible, three phases should follow the work initiated in this project:

Phase 1: The comparison of the results predicted by the model with the four different team structures (Six-Person multifunctional; four-Person functional; Hybrid; and Alternate functional) with the performance of teams using these different structures. This would provide a test of the specific assumptions proposed in the model and help improve its reliability.

Phase 2: The replication of the results presented in this report with a different microworld in order to generalize the findings and increase the ecological validity of the approach.

Phase 3: The validation of the capacity of the model to assist team design by testing its predictions of performance for real C2 teams in the ecological context of a rapid response planning exercise or integrated C2 experimentation.

Sommaire

Developing a framework for estimating the costs/benefits of teamwork in C2:

Richard Breton; Daniel Lafond; Sébastien Tremblay; Robert Rousseau; DRDC Valcartier TR 2010-225; R & D pour la défense Canada – Valcartier; Septembre 2011.

Introduction: Ce document présente un cadre théorique de modélisation pour l'estimation des coûts et bénéfices reliés à différentes structures d'équipe de C2. La stratégie proposée combine une analyse de tâche à une modélisation basée sur les données afin de supporter le besoin de design approprié d'équipes pour les situations militaires de C2.

Résultats: Une analyse de tâche hiérarchique a permis l'identification d'un ensemble de sous-tâches associées aux différentes composantes de la tâche simulée de C2. Une association tâche-agent basée sur les résultats de cette analyse a démontré des dépendances interpersonnelles entre les tâches et les activités associées aux différents agents (activités par rapport à la tâche, à l'équipe et aux interactions avec les outils). Un modèle mathématique, étalonné à partir d'une étude empirique impliquant deux structures d'équipe, a permis la quantification de l'impact de chaque élément de ces associations sur la charge de travail mental de chaque agent. De plus, le modèle spécifie les effets de cette charge de travail sur le niveau de performance de l'équipe en fonction des relations interpersonnelles.

Un impact majeur de ce projet concerne la démonstration de la relation entre des concepts déterminants du travail en équipe et l'efficacité de l'équipe variant en fonction de la structure de l'équipe. Cette démonstration provient de la comparaison des coefficients trouvés à partir de deux régressions multiples (pour l'équipe fonctionnelle et l'équipe multifonctionnelle) reliant alors la performance de chacune de ces deux équipes à un nombre de paramètres de prédiction pour l'efficacité de l'équipe.

Également, des différences et similarités importantes entre les deux structures d'équipe ont été observées, suggérant que certains aspects du fonctionnement de l'équipe peuvent changer de façon significative en fonction de la structure d'équipe. Les résultats démontrés dans ce rapport suggèrent que les besoins du travail en équipe et l'importance de différents facteurs d'équipe en général varient donc en fonction de la structure de l'équipe. Évidemment, la communication et la coordination sont deux composantes importantes du travail en équipe. Par contre, leur importance relative est affectée par la façon dont l'équipe est configurée. Par exemple, les résultats ont démontré que la communication était positivement corrélée avec la performance pour l'équipe fonctionnelle, mais négativement corrélée pour l'équipe multifonctionnelle.

Finalement, le modèle mathématique a démontré une capacité impressionnante à reproduire les résultats observés lors de l'étude empirique. Donc, à partir de ce modèle, il a été possible de simuler et prédire la performance de quatre autres types de structures d'équipe.

Importance: Le travail en équipe est souvent essentiel dans des environnements complexes et dynamiques tels que le C2. Dans les domaines des opérations militaires et de la sécurité

intérieure, il y a un intérêt croissant pour la recherche concernant les équipes avec l'intention d'améliorer leur efficacité par le réseautage. Plusieurs questions concernent l'optimisation de l'opérabilité inter-équipe et intra-équipe. Ce projet amène des découvertes intéressantes concernant ces questions.

Premièrement, puisque différentes structures d'équipe de C2 impliquent différents processus d'équipe, il semblerait inadéquat que les recherches futures se basent sur un modèle générique considérant un ensemble fixe d'une structure à l'autre de processus d'équipe pour prédire la performance. Le rôle ne semblant pas être le même d'une équipe à l'autre, un ensemble fixe ne peut donc pas permettre de prédire efficacement la performance en fonction des différentes structures d'équipe.

Deuxièmement, ce projet permet de définir le niveau de charge de travail mental individuel comme un élément clé pour prédire la performance de l'équipe. La corrélation entre le niveau de charge de travail mental perçue par les participants et le résultat de la modélisation (charge prédite) est étonnante. Ce résultat remarquable suggère que la métrique utilisée dans le modèle pour la charge de travail mental qui est basée sur l'association entre les tâches et les agents représente très précisément la charge de travail mental réelle des participants.

Perspectives: La possibilité d'utiliser ce modèle mathématique pour identifier, en fonction du contexte, la structure optimale d'une équipe ainsi que le nombre optimal d'agents dans l'équipe est prometteur. Pour rendre cela possible, certaines phases sont toutefois requises:

Phase 1: La comparaison des résultats prédits par le modèle pour les quatre structures d'équipe (six-personnes multifonctionnelle; quatre-personnes fonctionnelle; hybride; et fonctionnelle alternative) avec la performance réelle d'équipes basées selon ses structures. Cela permettrait de tester les hypothèses proposées par le modèle et d'augmenter sa fiabilité.

Phase 2: La reproduction des résultats présentés dans ce rapport avec un micro-monde différent. Cela permettrait de généraliser les résultats et d'augmenter la validité écologique de l'approche.

Phase 3: La validation de la capacité du modèle d'assister le design d'équipe en testant ces prédictions de la performance pour des équipes réelles de C2 dans un contexte écologique de processus de planification rapide ou des expérimentations sur le C2 intégré.

Table of contents

List of figures

List of tables

Acknowledgements

The authors would like to thank Dr David Bryant from DRDC Toronto for reviewing the manuscript.

1 Introduction

Teamwork is often essential in complex and dynamic environments such as command and control (C2). In the domains of military operations and homeland security, there is a growing interest in team research, with the intention to improve efficacy through the use of networking. There are important issues with regards to inter-team operability and intra-team optimization of performance. At the tactical level, the context of operations is often one of high constraints in terms of time pressure and uncertainty. Small teams of military units, security or emergency workers are often confronted with such situations in which they must work together in order to achieve safety-critical goals and mission success. In C2 situations, the expertise and resources required for the successful achievement of the mission most often go beyond the capability of a single individual. However, the addition of people in the execution of the tasks represents in itself an element of complexity. In the current project, the goal is to develop a methodology that will enable users to estimate the cost and benefits of teamwork in tactical C2 for intra-team activities and identify team structures that support optimal team performance.

The structure of a team may range from rigid, with clearly defined roles and a hierarchical chain-of-command, to flexible, where individuals all have similar capabilities, tasks are allocated flexibly, and decisions are made jointly by consensus. Different team structures may involve particular benefits resulting from the leverage achieved by combining individual capabilities in different ways. These structures impose teamwork requirements. Coordination and communication among team members come with a cost in performance. Some team structures may exacerbate teamwork requirements to the point that no benefits are observed, while others can maximize the benefits without entailing extensive interaction costs. Besides the context of operations and environmental constraints, the effectiveness of different team structures depends on this interplay between costs and benefits. Since this interplay is not well understood, the aim of the present work is to develop a model of the effects of the organizational structure on team performance.

In the following sections of this report, we will provide a background on relevant research (Section 2) on C2, team cognition and team structures and report different steps in the development of a methodology for estimating the costs/benefits of teamwork in C2 (Sections 3-5). Our methodology can be described in three parts:

- A data-driven analysis (reported in Section 3) focused on the experimental study of team effectiveness as a function of team structure.
- A task-driven analysis (reported in Section 4) focused on a hierarchical decomposition of subtasks. The analysis is complemented by an assessment of tools, information, triggering events and actions associated with each subtask.
- An integration of the data-driven and task-driven approach (Section 5), involving a task-to-agent mapping that characterizes the teamwork, taskwork and tool interactions for each agent and task dependency. This mapping forms the basis for a mathematical model calibrated on the experimental data and used to predict the effectiveness of different team structures.

2 Background

2.1 Command and control

According to Curts and Campbell [1], C2 can be defined as “the exercise of direction by a designated leadership over resources in the accomplishment of a mission”. Pigeau and McCann [2] define command as “the creative expression of human will necessary to accomplish the mission” and control as “those structures and processes devised by command to enable it and to manage risk”. While C2 is predominantly associated with military operations, it also applies to many non-military activities such as fire fighting, air-traffic control, nuclear power plant operations, hospital emergency rooms, and incident command in crisis management (e.g., rescue operations following a disaster).

Military C2 can be defined as the control of spatially distributed assets (e.g., sensors) as efficiently as possible in order to achieve tactical goals [3] and consists of:

1. information gathering and situation assessment;
2. identification or classification of the situation based on situations typically encountered;
3. proposal of a solution;
4. evaluation and refinement of the solution by projection of consequences and events into the near future; and
5. execution of the response and continued monitoring of the situation to ensure it evolves as desired [4].

C2 can take place at three distinct levels each having its own contextual characteristics:

- **A strategic context:** Decision making at the strategic level is about forming a comprehensive view of the situation, reasoning about its meaning, finding possible outcomes and then choosing what policy to adopt. It requires considering trends, long term effects and global outcomes. Strategic planning focuses on the overall context, not the specifics. In sum, it is about defining a general strategy to reach long term objectives. Collaborative decision making at the strategic level is removed from the action and generally occurs under low levels of time-pressure.
- **An operational context:** Operational decision-making requires more detailed planning based on the specifics of the situation. This level aims to coordinate tactics in order to reach strategic goals. Objectives are oriented toward a specific situation. Here, the time window is smaller than at the strategic level and the team is closer to the action (but still removed from it). Information management is an important aspect of operational decision-making, though the scope of situation is more restrained than at the strategic level.

- **A tactical context:** A tactical team is in the middle of the action and is focused on task execution. Tactical decision-making is therefore focused on the immediate situation and on the technical aspects of the actions to perform. Time is the essence and decisions must be made without complex reasoning and deliberation. There is little opportunity for extensive information gathering and management. Collaboration in this context is mainly about sharing awareness, mutual coordination, mutual support and the application of team training. This is the decision making level being focused on in the present report.

Figure 1 shows that the tactical, operation and strategic levels can be place on a continuum in which levels of decision-making, task execution, time-pressure and information load either increase or decrease. The strategic level is mainly about taking decisions based on the best information possible. At the other extreme, tactical decision-making must be quick and mainly leads to task execution rather than information management.

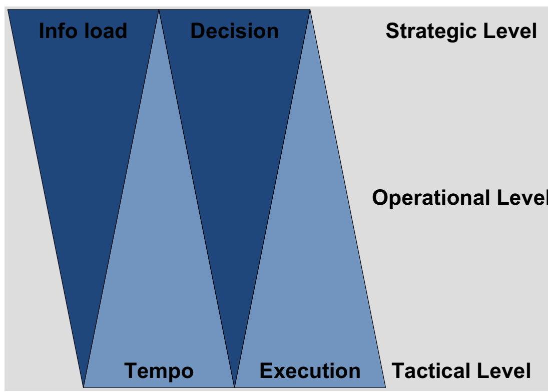


Figure 1: Levels of decision-making.

In the context of military operations, C2 is commonly described as the cyclic and continuous operation of four functions (see Figure 2): Observe-Orient-Decide-Act referred to as the OODA loop [5].

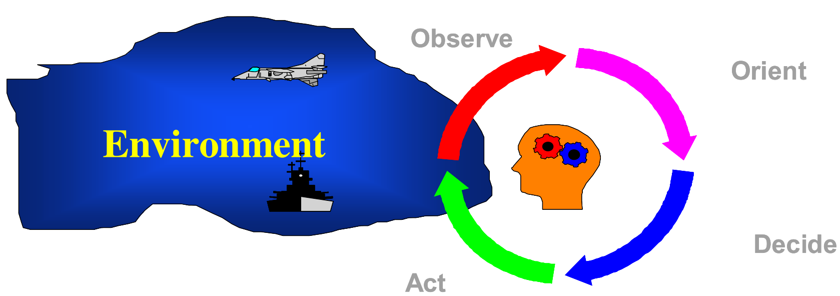


Figure 2: The classical version of the OODA loop model.

- *Observe* is to collect information about the environment (enemy position, status, intent, friendly forces position). The effectiveness of this phase relies on the amount, quality, appropriateness, and timeliness of information.
- *Orient* is to develop knowledge and judgments about the situation. This is where the awareness of the situation is developed and is based on cognitive processes of knowledge development. The ability to convert data into information that develops knowledge that supports understanding is what is taking place in this cognitive process.
- *Decide* is the course of action taken that develops in some plan. The ability to make sound and timely decisions is an important part of effective command and control. The ability to make good decisions faster considering the uncertainties provides an advantage.
- *Act* is taken to convey the commander's intent through orders. This may be through detailed orders or by passing along high level objectives. This also includes monitoring the execution of operations that required information in the "Observe" phase of command and control.

The OODA can be understood as a simple control system [6]. It stresses the importance of two critical factors in the environment, time constraints and information uncertainty, on the execution of the decision cycle. In order to deal with the time constraints, the phases of the loop must be executed as quickly as possible. To reduce the information uncertainty, they must be performed accurately. The antagonistic relationship between these two factors is commonly referred to as the speed-accuracy trade-off [7].

Decision-making at the strategic, operational or tactical level can be described by the OODA phases. However, these three levels of decision-making are characterized by different levels of time pressure and the amount of information that can be processed in order to cope with the situation uncertainty.

2.1.1 Teamwork in C2

Historically, C2 has been seen as a hierarchical process of commanders directing their subordinates on the battlefield (though generalized command and control also has many non-military applications as well). However, more recently there has been an increasing appreciation of the distributed nature of information collection. Often, decisions must be coordinated laterally between multiple units involved, and occasionally there is a need to push decisions further down to smaller units closer to the battles, which have a better sense of tactical opportunities and consequences of actions. Hierarchical command is now even viewed by some as inflexible and sub-optimal.

Teamwork is often associated with C2. Many definitions of teamwork have been proposed, but one common element is that teamwork is about several individuals working toward a shared goal (see [8]). For instance, McIntyre and Salas [9] describe a team as a "set of two or more individuals who interact interdependently and adaptively to achieve specified, shared and valued objectives". Each team member thus has to perform some tasks associated with his or her role within the team. In order to make an optimal decision information has to be effectively merged

among team members. Salas, Bowers, and Cannon-Bowers [10] assert that although significant advances have been made in understanding team processes, much remains to be done. Indeed, a lack of consensus regarding the delimitation and conceptualization of processes and behaviours critical for team effectiveness is evident in the literature on teamwork (see [11; 12]).

While some principles of teamwork may turn out to be universal, there is a growing consensus that factors of team effectiveness are context-dependent. This idea also relates to the basic tenet of the study of situated cognition: “Human intellectual resources engage with, and cannot usefully be seen as separate from, the physical resources in the world in task performance [13]”. Traditional experimental studies tend to ignore the situated and organizational features of work. People use a large range of resources in their work environment. These resources and tools are typically removed in laboratory settings so that they do not interfere with the “controlled variables”. These resources and the interactions between them are critical for understanding much of our behaviour in actual work settings [14].

Consequently, there is a growing need to understand teamwork and the processes or factors that affect the team performance. These processes or factors are context-dependent. Then, it is important to develop an approach to support the optimal team structure based on the context in which teamwork occurs.

2.1.2 Fields of study of teamwork

The term “teamwork” can be found in the management, psychology and human factors literature, whereas “collaborative work” is most often employed in the technology-related literature. Teamwork is an active research topic in many fields, particularly in distributed artificial intelligence (including multiagent systems and computational organizational theory) and in the field of dynamic decision making.

Distributed artificial intelligence (DAI) refers to the design and application of multiagent systems, in which interacting intelligent agents pursue a set of goals or perform a set of tasks. Agent operations can be affected by interactions with other agents and humans. The main interaction patterns in multiagent systems are goal and task-oriented coordination, in cooperative and in competitive situations. DAI’s long-term goal is to develop methods enabling agents to interact and to advance the understanding of interactions among intelligent entities whether they are computational or human. Multiagent systems (MAS) study networked systems composed of distributed agents (humans, robots, computational problem solvers) that can deliberate, predict, communicate, and cooperate [15]. MAS can be characterized as having:

1. no explicit global control;

2. distributed resources, expertise, intelligence, and processing capabilities;

3. an open environment full of uncertainties; and

4. an emphasis placed on social agency and social commitments.

The Computational Organization Theory (COT) uses models and simulations to analyze organizations and their processes, adopting concepts from DAI and from the work of

organizational theorists. Advances in COT are mainly achieved through the use of multiagent modeling techniques, where intelligent agents generally cooperate together to achieve some collective goal. Agents can take specific social roles, possess a given set of cognitive capabilities, and have particular tasks to accomplish. COT examines how organizations composed of people, artificial agents, or both should be coordinated and how tasks should be distributed. Some of the main research topics in this area are organizational design, knowledge sharing, learning, and adaptability. Formal concepts and specific measures of organizational design are taken from research in the areas of coordination [16], social networks [17] and distributed control [18].

Team decision making generally occurs in dynamic task environments. Dynamic decision-making research investigates how people control dynamic, complex, real-world systems [19].

A dynamic system is one in which:

1. a series of activities are required to reach/maintain the overall goal;

2. activities depend on the outcome of previous activities;

3. task parameters are continuously varying in response to changes; and

4. tasks are accomplished in real time.

Dynamic environments involve a variety of cognitive processes such as monitoring, recognition, causal learning, search, planning, judgment, and choice [19]. The ability to coordinate these processes while performing under time constraints is a key to achieving system control. The decision makers must analyze the state of the system and attempt to influence existing processes in order to achieve a desired state [20]. This type of environment is often characterized by changing conditions, time pressure, uncertainty and an overwhelming amount of information to process. A multitude of stressors may thus be identified: multiple information sources; incomplete, conflicting information; rapidly changing, evolving scenarios; time pressure; high work/information load; and threat (see [21]).

2.2 Teamwork and cognition

For Cannon-Bowers, Tannenbaum, Salas, and Volpe [22], team processes refer to behavioral and cognitive procedures required to perform the task so that the team goal can be attained. Comparatively to individual work, teamwork involves unique behaviours, such as coordination and information sharing. In that context, behaviours specific to teamwork are critical, since individual behaviours are not sufficient for team effectiveness [23]. As pointed out by Cannon-Bowers and Salas [24], teamwork behaviours are more than just individual abilities applied to team tasks. In fact, because they cannot be easily quantified–as opposed, for instance, to team performance–team behaviours constitute one of the most difficult elements to capture. Consequently, researchers in the team domain have struggled to identify and operationalize the critical behaviours that allow a team to work effectively [25].

2.2.1 Teamwork vs taskwork

A distinction is often made between taskwork and teamwork. Individuals will have two main types of behaviour: those that are related to the individual tasks, referred to as taskwork; and those that are related to team members in order to coordinate tasks and share information, referred to as teamwork [22]. Teamwork is about working toward a shared goal (e.g., [26]). Those behaviours of team members that engender a sharing of information and a coordination of activities are collectively called teamwork. Teamwork is a behavioural construct; it is a composite of behaviours that team members exhibit to support each other in their tasks.

2.2.2 Teamwork behaviours

A long list of teamwork behaviours are identified and described in the literature, and all seem more or less related to team performance. In the various taxonomies (e.g., [25; 27; 28]) and models (e.g., [29; 30; 31]) that have been put forward, teamwork behaviours most often include communication, adaptability, coordination, performance monitoring/feedback, team leadership, team situation awareness and decision making, conflict resolution, information management, and task distribution.

Salas et al. [12] point out that owing to the lack of consensus among taxonomies and models, there is a need to reduce the number of factors that are crucial to teamwork. Based on an exhaustive survey of the literature, they propose five core components to teamwork: team leadership, performance monitoring, backup behaviour, adaptability, and team orientation (that is, the inclination to consider other team members' input and behaviours in the execution of team tasks and to improve individual performance by doing so). While acknowledging that other variables can affect teamwork, Salas et al. argue that these five elements are the ones with the greatest impact on team performance and that are identified as important to teamwork in a majority of taxonomies. The authors also suggest that the successful enactment of these components requires the presence of three coordination mechanisms between team members: shared mental models, closed-loop communication, and mutual trust.

Rousseau et al. [11] propose a comprehensive framework of teamwork behaviours that is structured hierarchically. The authors assert that teamwork behaviours hold two main functions, regulation of team performance and management of team maintenance, which are divided into sub-categories of teamwork dimensions. While management of team concerns personal and inter-personal factors (psychological support and conflict management), regulation of team performance integrates teamwork behaviours found in several other taxonomies into four dimensions, that is, preparation of work accomplishment (e.g., mission analysis, planning), task-related collaborative behaviours (e.g., coordination, information exchange), work assessment behaviours (e.g., performance monitoring), and team adjustment behaviours (e.g., backing up behaviours). Rousseau et al. also include a sequential component into their framework, such that teamwork dimensions are organized according to when they will presumably achieve their intended effects and contribute to team effectiveness.

While most teamwork models and taxonomies lack of consensus over the factors that impact teamwork, all acknowledge the importance of the coordination and the communication among team members. These two critical factors for teamwork can be described as follow:

- **Coordination:** Coordination generally refers to the merging and mutual adjustment of activities between team members on one hand, and between team members and tools/resources on the other hand, in accordance with the task to be executed [32]. Situating coordination in a context of complex and dynamic situations, Espinosa, Lerch, and Kraut [33] propose that coordination consists in efficiently managing dependencies between tasks, resources and team members. Cannon-Bowers, Salas, and Converse [34] add that shared mental models are a key element in explaining how a team coordinates, adapts and anticipates, as they provide a set of knowledge and expectations about others' behaviours.
- **Communication:** A common definition of communication is the exchange of information between team members. Communication is a key element in team functioning because it provides information, establishes interpersonal relationships and maintains attention to task monitoring. When communication is related to the task (commands, orders, tactical communication) it is positively related to performance, whereas poorly performing teams seem to have more difficulty dealing with uncertainty (making more questions and giving fewer orders) and to emit more statements unrelated to the task (e.g., [35; 36;]). This is consistent with the findings of Cannon-Bowers et al. [22] suggesting that extensive communication can be disruptive of team performance. Communication is inextricably linked with other team process, such as sharing knowledge, team coordination and adaptation. Due to such complex relation, empirical studies of the relationship between communication and performance do not show a consistent pattern. MacMillan, Entin and Serafty [37] report evidence that communication and coordination are highly interdependent: reducing coordination requirements reduces the need for communication and team performance tends to increase in these conditions.

2.2.3 Impact of workload on teamwork

Most research relating to workload is based on individual workload and very few studies concern team workload. For this reason, most of the knowledge concerning team workload comes from research related to individuals. Bowers et al. [38] define team workload as the relationship between the finite performance capacities of a team and the demands placed on the team by its performance environment. Workload can be operationalized in two different ways; it can be viewed either as time pressure or as resource demand.

Team workload is more complex than individual workload in that team members must execute two kinds of work at the same time. In addition to having to carry out their own specific tasks correctly, members must coordinate their tasks with other team members and communicate with them in order to reach their common objectives. This refers respectively to the concepts of taskwork and teamwork mentioned earlier.

Bowers et al. [38] draw a portrait of various variables which can impact workload in a team context. While this list is not exhaustive, the authors sustain that these variables seem to be the most influential:

- **Coordination:** This variable is fundamental to both taskwork and teamwork. There is no clear evidence on how coordination actually moderates the effects of workload, mainly because this variable is difficult to manipulate in an experimental context

[38]. Research seems to show that higher coordination requirements increase operator workload.

- **Communication:** Tasks which require a lot of communication between team members produce an additional demand for the operators [39]. Consequently, high communication requirements are associated with high workload.
- **Team experience and maturation:** When team members are used to work with the same information and on the same tasks, information processing can change from controlled processes to automatic processes, which require less resource from the operators. Moreover, when an operator has more experience, communication with other team members is more effective. Thus, team experience and maturation decrease workload [38].
- **Team training:** Training seems to have a high influence on workload. However, there is no direct evidence of this relation. Because training increases team performance, it is suggested that operators have more resources and workload is decreased.

Workload is a critical variable in task allocation. In studies on task allocation, the level of workload usually determines conditions of the experiment (and not the other way around) and workload is kept constant from the beginning to the end of the simulation [40]. Another key topic in relation to task allocation and workload is the study of the interaction between the level of workload and the organizational structure of the team. As such, Urban et al. [41] test different levels of workload (low, baseline, high) on two organizational structures (hierarchical and non-hierarchical). They find no interaction between the level of workload and the organizational structure (note, however that they did not consider workload *distribution* across individuals). In another study, Urban et al. [42] found that a hierarchical structure performed worse than a non-hierarchical organization, especially in high workload conditions.

2.3 Team structure

Although there is good theoretical agreement that the structure of a team greatly influences interdependence relations and team functioning, there is relatively little empirical work that directly addresses the relationship between team structure and team performance. There is no clear distinction in the literature between task allocation, role allocation, team structure, organization and team architecture. The main idea behind all these concepts is the distribution of task demands among team members in such a way that the organization is as efficient as possible. Below, we discuss communication structure, structural contingency theory, and focus on the distinction between functional and multifunctional (or cross-functional) team structures and approaches to team design.

2.3.1 Communication structure

Marks, Zaccaro, and Mathieu [43], studied three-member teams in a Tank War-Game simulation. Judges categorised communications into six classes: 1) assertiveness, 2) decision making and mission analysis, 3) adaptability and flexibility, 4) situational awareness, 5) leadership, and 6) communication. The quality of team communication was rated on a scale ranging from 1

(extremely poor) to 7 (extremely good). Results showed that high quality of communication on all dimensions was positively related to good performance on the simulation task (see [23], for similar results). In teams, communication and information exchange usually follow regular patterns. Figure 3 presents five prototypical patterns:

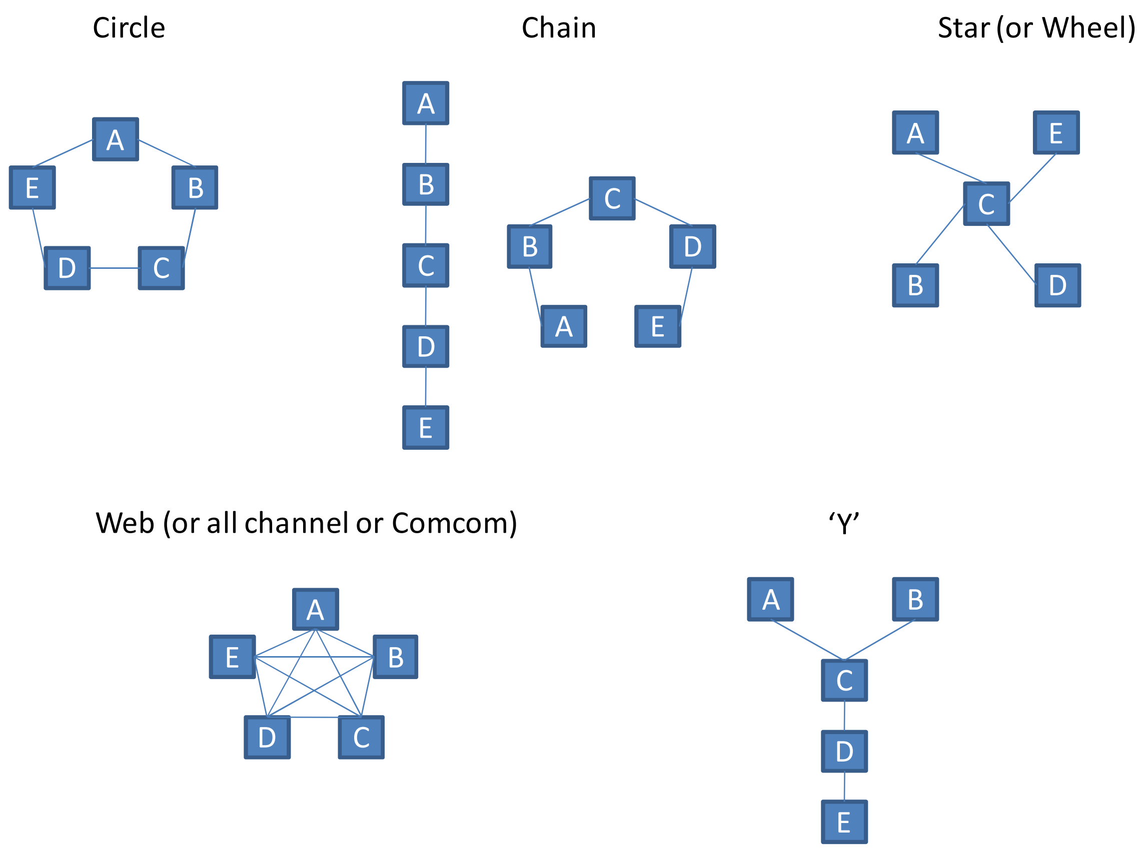


Figure 3: Five prototypical communication patterns.

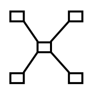
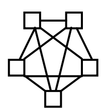
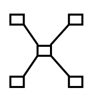
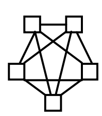
These five diagrams represent the major communication structures [44]. Each of these communication networks has implications for a number of team features – among others, the style of leadership adopted and the ability of individuals to contribute to collective decision-making. The characteristics of the different communication networks are determined by the extent of 'independence' and 'saturation'. Independence refers to the opportunities for team members to take action and to solve the problem without relying on the assistance of others, while saturation occurs when the task places an excessive information load (or other demands) upon a member of the network, which leads to inefficiency. In a centralised network, the central person is more likely to experience saturation. Overall, the effectiveness of the team will be influenced by the appropriateness of its communication pattern for the type of task to be accomplished [45].

Various characteristics differentiate the communication structures, and the pattern of communication adopted has significant implications for the work of the team, the degree and quality of debate within the team, and the ways in which any decision is taken. For instance,

communication networks can be distinguished based on the centralisation of the information exchange. As presented in Table 1 (below), whether a communication pattern is centralised or not can influence the information flow, the information load as well as the resulting performance. Generally, centralised networks tend to be superior on simple tasks whereas decentralised networks are superior on complex tasks. The presence or not of a central person in the network represents another factor that characterizes the communication structure. Hence, in both the Star and Y patterns, there exists a focal person through whom the essentially linear communication patterns pass. In patterns such as the Circle and the Chain, the information flow is still linear but with no central person.

Table 1 presents the characteristics of the information and performance outcome for centralised and decentralised networks (from Mullins, [45]).

Table 1: Team performance as a function of communication network and task complexity.

Type of task / network		***Information flow***	***Information load / task completion***	***Performance outcome***
		Simple task		
Centralised networks (e.g., Star)		To central person	Central person can perform task alone	Good
Decentralised networks (e.g., Web)		All around network	No one person has all the required information	Poor
		Complex task		
Centralised networks (e.g., Star)		**To central person**	Central person becomes saturated	Poor
Decentralised Networks (e.g., Web)		All around network	No one person becomes saturated	Good

A contrast can be made between open-channel patterns, such as the Web network pattern, which has ten channels, and closed channel systems such as the Chain pattern, with only four channels. In a flexible environment, there are several factors that affect which pattern a team may adopt. These include whether or not there is an authority figure or nominated leader present, the characteristics of the task, such as time pressure and interpersonal dynamics of the team members. In face-to face teams, Chains and Ys are uncommon: Stars, Webs and Circles, generally a little modified from the pure type, are the usual patterns. The pattern of communication itself affects how accurately messages are transmitted and received, the level of task performance and the amount of satisfaction experienced by the team members.

In a military context, the structure of communication is highly dependent on the structure of authority. A linear pattern like the Chain is more probable as it corresponds to the usual chain of command found in most military organizations. This is also the case in a coalition, although the complexity of the context may imply more than one type of communication pattern. Indeed, as there are at least two global levels of command in a coalition (a more political level and a more strategic/tactical level), the information exchange within each level and between the two levels may be based on different communication structures.

Leader-centred teams such as Stars or Ys are likely to perform specific tasks more rapidly than shared leadership teams such as Webs, but the latter appear to cope more easily with change and to sustain higher levels of member morale. If the task requires swift action with a centre-out direction and limited pooling of information and expertise, the Star will be the most effective. However, given a task for which all members' contributions are needed, and team morale needs to be sustained over a long period, the Web may well work the best. Centrality (by circumstance) can help to determine the leadership role: Positions that are lower than others in communication centrality lack much opportunity for action and influence and can feel excluded, and therefore may be less likely to take on a leadership role.

Baron and Greenberg [46] as well as Shaw [47] suggest that the Wheel would produce an effective result when simple tasks are involved. In those cases, the central person could undertake the task alone with the necessary information provided by the peripheral members. They also propose that an all-channel pattern like the Web would produce a poor result in such situations because the flow of information circulates all around the group with no single person collating it in terms of decisions necessary. The authors point out that for a complex task/problem, these outcomes would be reversed. In complex decision situations, it is usually necessary to have the flow of communication around the team to encourage 'richness' in analysis and debate as well as limiting the demands placed on the leader to find a solution.

2.3.1.1 Network-centric organization

Dekker [48] criticizes the fact that the network-centric warfare literature advocates self-synchronisation rather than centralisation of command and control activities without considering that there may be specific circumstances in which one organizational structure is more effective than the other. Using an agent-based simulation, Dekker compared the performance achieved using a centralized organizational structure in which a *command* agent elaborates the plan for solving the problem, or a decentralized organizational structure in which agents self-synchronize by exchanging messages. This study examined the efficiency of these two structures in three different problem-solving tasks. For each task, the level of time pressure and network quality (the speed of message exchange) was varied in systematic way in order to ascertain the generality of the simulation's outcomes.

The simulation environment was populated by simple communicating agents providing an abstract representation of communication and synchronization between military entities. The agents faced three computational problems of increasing difficulty:

- *The selection problem.* One agent is to be assigned to a task and the group must select the best-qualified agent. In Dekker's abstract simulation, each agent simply has a randomly assigned suitability score.

- *The target assignment problem.* This task involves 16 or 64 agents (i.e., *small* version and *large* version) and 16 targets. The most suitable agent must be assigned for each target. In this relatively simple version of the task, the most suitable agent is the one closest to the target. Figure 4 illustrates this problem.

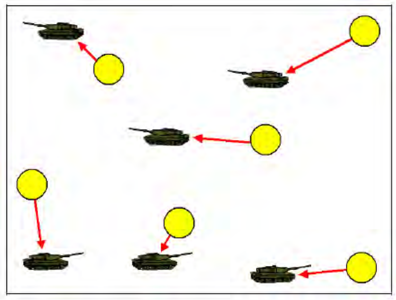


Figure 4: The target assignment problem (from [48]).

- *The "travelling general" problem.* This is actually the travelling salesman problem, but with a general. In this task a General must visit all agents in turn, and return to his starting point (see Figure 5). The objective is to find the shortest path that may be traveled in order to "minimize the risk" to the general.

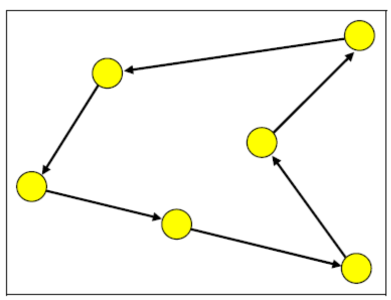


Figure 5: The travelling general problem (from [48]).

The simulation results demonstrated that for the selection problem, the centralised and self-synchronised approaches work equally well, but the self-synchronised approach has the advantage of being fault-tolerant (the network is resilient to agents going off-line). For the small version of the target assignment problem, when time-pressure is low, the centralised approach can provide a "knowledge edge" by finding the best possible solution. Nonetheless, the distributed process can perform as well as the centralised process in many versions of the target selection task, and actually performs better when there is great time pressure and a fast network. Furthermore, the decentralised structure has the advantage of fault-tolerance: it can continue to operate even though some agents get disconnected from the network. For the travelling General problem, the centralised and decentralised structures had comparable results, except when time pressure was very high and network communications were very fast. In that case, the

decentralised structure found shorter travel paths than the centralised structure. Based on these findings, Dekker [48] concluded that a combination of fast network and extreme time pressure corresponds to the type of situation in which Network Centric Warfare is most appropriate.

Finally, Dekker investigated the effects of using a hierarchical structure in the large version of the target assignment problem. Hierarchies constitute a compromise between centralisation and self-synchronisation and are widely used in both military and bureaucratic organizations. The 64 agents were organized into 16 teams (i.e., a multiteam system) and 5 additional command agents completed the hierarchical structure (see Figure 6). This organization solves the target assignment problem using a "divide and conquer" strategy. The higher-level agents divide the area of operations into rectangles containing only four targets (see Figure 7). This strategy decomposes the large target assignment problem to sixteen small target assignment problems.

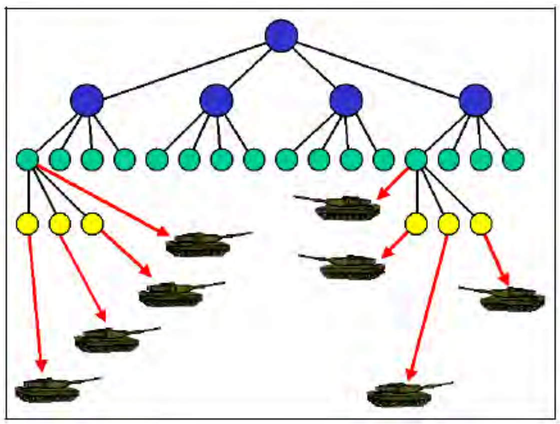


Figure 6: Hierarchy for the target assignment problem (from [48]).

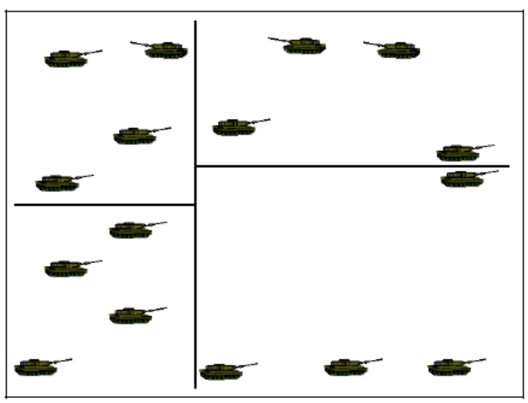


Figure 7: "Divide and Conquer" for the target assignment problem (from [48]).

Results showed that the hierarchical organization generally performed worse than the centralised and distributed structures. Dekker explains that the hierarchical structure allowed little opportunity for coordination between the "leaves" of the tree. He concludes that performance in hierarchical organizations could be improved by allowing coordination between the different

teams of agents (i.e., engaging in inter-team coordination), using either self-synchronisation or a centralised coordination mechanism.

2.3.2 Structural contingency theory

A great deal of research on organizational structure is based on the structural contingency theory. This theory stipulates that there is no single best way to organize a team; what is important is the optimal fit between the organization's structure and its environment. Hollenbeck's [49] theory on organizational structure identifies three fundamental characteristics of team structure: centralisation, departmentation and adaptability:

- ***Centralisation:*** It relates to the extent to which responsibility and authority are distributed among members. A centralised team typically includes a leader with the responsibility to command other team members. An advantage of centralisation is that it ensures coordination and efficiency due to the strong element of leader control. In a decentralised team, responsibilities and roles are distributed among team members. An advantage of decentralisation is that it ensures quickness and learning due to the fact that there is no hierarchical structure that individual team members must go through in order to make decisions.
- ***Departmentation:*** Organizational structures can be divided in two categories: functional and divisional. In terms of task allocation, a functional structure refers to an organization where there are many work units specialised in one aspect of the production. All units put together generate a finished product. This type of organization creates specialised roles where the level of interdependence between work units is high. Divisional organizations consist in each unit possessing the skills and/or resources required to solely generate the product. Such work units are capable of working relatively autonomously.
- ***Adaptability:*** It refers to the degree to which teams are able to adapt their structure to take advantage of the characteristics of a certain type of structural organization (e.g., centralised/functional versus decentralised/divisional), depending on the task's requirements and context. Adaptable teams are able to adjust their structure to the environment they are facing, whereas fixed teams tend to maintain one type of structure.

Hollenbeck [49] extended the basic principle of structural contingency theory. He describes a theory with two complementary types of "structural fit": (1) the fit between the organization's structure and its environment (called the *external fit*), and (2) the fit between the organization's structure and the team members' skills, traits and expertise (called the *internal fit*).

2.3.3 Functional vs multifunctional

Price, Miller, Entin and Rubineau [50] tested the impact of team organizational structure (functional versus divisional) on performance, using humanitarian relief scenarios. In a functional team structure, individuals have different complementary roles: Team members are specialized and interdependent. In a divisional team structure, individuals have multifaceted roles and are relatively autonomous, enabling them able to divide the operational space into distinct areas of responsibility. Divisional teams are a particular case of a multifunctional team structure in which

the area of responsibility is divided a priori rather than shared or divided spontaneously during the course of a mission. Results show that functional structures provide a higher performance, require less time to initiate tasks and show more coordination. They suggest that a functional structure is best because of the relative predictability of the humanitarian task environment. They conclude that if a mission poses an uncertain and unpredictable environment, it would be better to employ a divisional organization structure at first, but as the mission becomes more known and predictable, the organization's efficiency could be improved by making a transition to a more functional organization.

Diedrich et al. [51] evaluated the efficiency of the organizational structure (divisional vs. functional) in relation to mission requirements, using simulations implemented in the Distributed Dynamic Decision making (DDD) environment. Their findings reveal that functional teams tend to have a slight advantage in offensive operations, while the divisional teams tend to have a slight advantage in defensive operations. However, coordination and situational awareness were not better or worse across the two types of team structure.

2.3.3.1 Asymmetric adaptability

Moon et al. [52] suggest that studies concerning organizational structure are too static; that is, team members are assigned to a functional or divisional structure at the beginning of the task and the structure remains the same until the end. However, organizations may need to change their structure online in response to environmental changes. Therefore, these authors aim to test the adaptability aspect in Hollenbeck's theory [49]. They use a DDD simulation to study the adaptation process when changing from a functional to a divisional structure and from a divisional to a functional structure. Four-member teams switch between these two stages, and performance is measured in terms of number of points accumulated for the two stages. The authors then calculate the difference between the two stages to determine the level of adaptation. They conclude that adaptability is like a one-way street: it is easier and more natural to switch from a functional to a divisional structure than the opposite. The authors suggest that it is more natural because it reflects an increase of task scope for team members over time and because norms developed in divisional structures regarding communication are counter-productive when switching to the other structure. It appears that it is easier to switch from a functional to a divisional structure because communication and coordination are key elements for functional structure. Also, when the first scenario is divisional, there is a high level of independence and performance is affected by switching to a structure with a lower level of independence.

2.3.4 Team design

Prominent work on team design stemmed from the *Manning Affordability Initiative*, sponsored by the Office of Naval Research. The project involved complementary experimental and modeling initiatives. First, a human-in-the-loop experiment using an air defense warfare scenario measured the effectiveness of eight 8-person team working with a standard watchstation design and compared it to the effectiveness of six teams of 4 individuals working with an advanced watchstation design. The reduced teams working with the advanced watchstations with a human-centered design performed either as well or better than the baseline teams [53].

Data from this human-in-the-loop experiment were used to calibrate and validate three human performance models used in synergy to model individual and team performance: Team Optimal Design (TOD), Integrated Performance Modeling Environment (IPME), and GOMS Language Evaluation and Analysis tool (GLEAN). Here, we will focus on the TOD methodology since it is the most relevant for modeling the effects of team structure.

TOD [54] is a methodology for helping designers of man-machine systems to model team performance and to perform trade-off analyses that systematically vary team size, the capabilities of team members, their responsibilities, their technologies, mission demands, and other factors. TOD is based on a multi-phase allocation model that consists of three parts [55]:

1. the tasks and their interrelationships (the "mission")

2. the resources needed to accomplish those tasks

3. the human operators who constitute the team

Figure 8 illustrates these three parts and the multi-phase allocation.

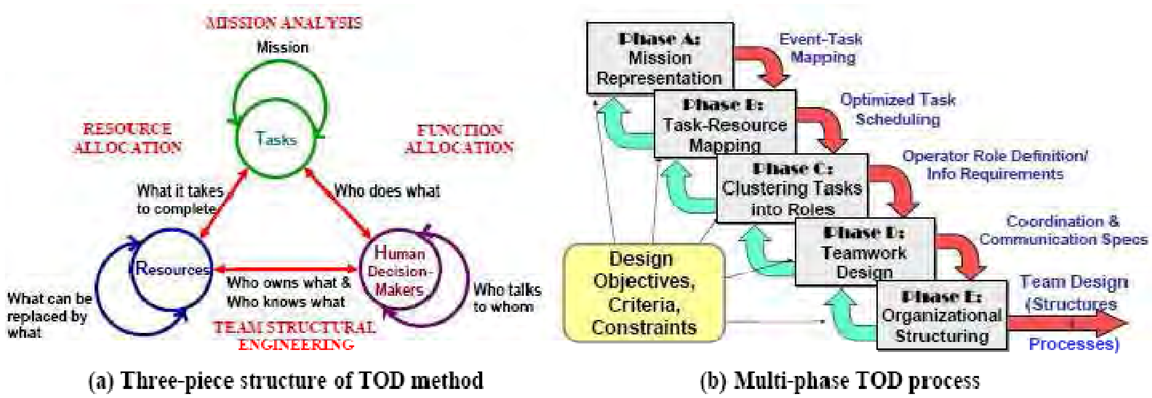


Figure 8: Team optimal design methodology (from [55]).

Kieras and Santoro [56] discuss the lessons learned from computational modeling attempts performed during the Manning Affordability Initiative project. Here are some remarks on the key challenges of this approach, stating that validating a model against data may be impractical:

> "Research on GOMS (Goals, Operators, Methods, Selection rules) and other modeling methodologies has usually tested the validity of the model by comparing its predictions to empirical data collected with actual human users in the same tasks and interface. […] But a GOMS model is based on a task analysis that identifies the user's goals and procedures, and can be wildly inaccurate if the task analysis is wrong. The usual way to identify such an

> error would be to compare the model's predictions to empirical data. However, the whole rationale for modeling human performance is to reduce the amount of empirical data collection needed to arrive at a usable design; clearly if validating the model requires as much data collection as user testing, there is little point to doing modeling. We discovered that the situation was actually more serious: in this very complex task, it was actually impractical to collect enough data to credibly validate a model" [56].

The solution proposed by Kieras and Santoro is to forego empirical calibration and validation and instead to have subject matter experts criticize the behavior of the model.

> "A scientifically-sound attempt to validate a model for the task would require larger sample sizes, multiple scenarios, and more experimental control over team procedures along with the same equipment and real test users. The huge expense of such an effort means that it could never be done" [56].

We suggest that the problem of model calibration and validation using experimental data highlighted above could be resolved by developing simpler and more tractable computational models. Computational GOMS models and complex cognitive architectures [56] as well as the TOD and the IPME methodologies described in Freeman et al. [53] are currently limited by their great complexity. Such models attempt to characterize processes and subtasks with such detail that estimating the numerous unknown parameters appropriately would require an excessively large number of experimental manipulations and measurements. This problem is similar to the notion of "sample complexity" in machine learning: the more complex the model, the more examples (i.e., constraints) it requires in order to make reliable predictions. We suggest that these computational methods should be more focused in order to model specific problems more effectively and reliably.

2.4 Costs and benefits of teamwork

The preceding sections of this report clearly demonstrated that teamwork is a multi-facets concept that is affected by the environment in which teamwork occurs. The complexity of teamwork raised the problem of identifying universal teamwork behaviours required for optimal team performance. These sections also showed the variability of the impact of workload in function of the team structure.

Different team structures have some disadvantages and some advantages whose impact depends on the task to perform and the environmental conditions. Consequently, the prediction of team performance or the identification of the optimal team structure depending on the task to perform or the environmental condition represents a challenge for the scientific community. A principled approach is needed to model the effects of team structure on team effectiveness.

2.4.1 Proposal

The purpose of the present project is to develop a method for predicting the effectiveness of different team structures. The method we propose for estimating the costs/benefits of different team structures combines two distinct approaches:

1. A *data-driven* approach, based on the analysis of team performance in a simulated task

2. A *task-driven* approach, based on the analysis of the C2 task, teamwork requirements, and tool interactions.

We submit that modeling the cost/benefits of teamwork requires a representation of the set of subtasks associated to each team member, of the set of tools required by each agent to accomplish his role and of the nature of team interactions. Manipulating team architecture is assumed to influence task difficulty in terms of *workload* by altering:

1. Each human agent's specific *taskwork requirements* (e.g., information that must be gathered, units to control, decisions to make);

2. The extent to which each agent must *interface with tools* (e.g., necessary interactions with specific panels of the interface or with input devices);

3. The overall *teamwork requirements* (e.g., communication and coordination work that arises when interdependent tasks are distributed across agents).

First, we will characterize the key differences between functional and multifunctional structures in order to explain how these structural factors lead to differences in team performance. We will perform a task-to-agent mapping that builds on the results of the Hierarchical Task Analysis (HTA). This mapping will enable us to identify interpersonal task dependencies and the types of activities that must be performed by each agent (taskwork, teamwork and interaction with tools). The task-to-agent mapping will provide the basis for assessing the relative workload of individuals in each team structure. Second, these structural factors will constitute inputs to a mathematical model designed to predict team effectiveness as a function of team structure. The mathematical model will relate team structure to team effectiveness using a construct relevant to all team structures: the workload of each individual in terms of teamwork, taskwork and tool interaction.

A similar multi-step methodology has been developed by Freeman et al. [53] in the context of C2 in naval air defence warfare. However, we argue that the computational GOMS, TOD and IPME models [53; 56], described earlier are unnecessarily complex and that this can seriously limit their reliability when calibrated on limited experimental data. The time, effort, expertise and cost required to develop and apply these models may be greater than necessary. For example, Levchuk et al. [55] model task effectiveness using many variables related to individual characteristics such as initial incompetence, learning and memory (retention of learning). These free parameters are not essential to predict the effectiveness of various team structures and they may provide too much flexibility to these models, thus increasing the risk of noise overfitting [57].

The present project proposes a new framework specifically focused on estimating the costs and benefits of teamwork because no prior framework is currently capable of providing reliable quantitative estimates of team effectiveness using a relatively simple and tractable approach.

2.4.2 Methodology

The proposed methodology for the data-driven part of the analysis is to perform a microworld experiment using a simulated C2 task for teams and manipulating team structure in order to measure team performance and various teamwork processes such as communication and coordination. Microworlds are task environments that are used to study behaviour under simulated conditions within a laboratory setting [58]. They retain the basic or essential real world characteristics while leaving out other aspects deemed superfluous for the purposes at hand. Microworlds offer the great advantages of experimental manipulation and control, without stripping away the complexity and the dynamic nature of the task. As in real world tasks, participants in microworld experiments have to choose between different alternatives in order to reach a goal (i.e., dynamic decision making and complex problem solving).

We opted for the C3Fire microworld as our testing platform [59; 60]. *C3* stands for *command*, *control* and *communications.* C3Fire is a functional simulation tailor-designed to investigate tactical C2 in small teams, though the actual microworld simulates firefighting rather than military operations. C3Fire seems best suited for the functional simulation of tactical C2 operations:

"The C3Fire microworld generates a task environment in which a group of people cooperate to extinguish a forest fire. It can be viewed as a command, control and communication simulation environment that can be used for the investigation and training experimentation of team decision-making and team Situation Awareness (SA). The [forest fire fighting] domain [...] is of subsidiary interest and has been chosen because it creates a good dynamic environment [...] It is possible to view the generated session as a simplified version of the work tasks and the division of labour conducted in an emergency task or a military task on a tactical level" [60].

C3Fire is appropriate for a functional simulation of military C2 since it involves time-pressure, uncertainty and teamwork: three key considerations for tactical C2 teams. Like tactical C2, the simulated task requires dynamic team decision making. It involves regulating a dynamic system where: 1) a series of activities are required to reach/maintain the overall goal; 2) activities depend on the outcome of previous activities; 3) task parameters are continuously varying in response to changes; and 4) tasks are accomplished in real time.

The proposed methodology for *task-driven* modeling is based on HTA [61; 62; 63; 64]. We selected HTA because it is a widely used, generic approach that forms the basis of a number of more specialized methods. HTA is readily understandable and provides few constraints on the analysis. While the HTA will provide an informative decomposition of taskwork, it will not identify activities related to teamwork. For that, a novel approach will be presented: a task-to-agent mapping that will use the results of the task analysis to characterize the taskwork, teamwork, interaction with tools and interpersonal dependencies that follow from specific task allocations and role assignments.

The final part of the methodology is to integrate results from the data-driven and task-modeling components of the methodology to produce a mathematical model characterizing the relationship between team structure and team performance. The mathematical model quantifies the impact of each element of the task-to-person mapping on individual workload and specifies the functional relationship between individual workload and team performance while taking into account task dependencies between team members. Once calibrated on experimental data, the model can be used to predict the performance of other possible team structures on the same task.

2.4.3 C3Fire microworld

The C3Fire microworld is a simulation of a complex and dynamic task in the firefighting domain. It is considered dynamic because the fire evolves autonomously over time, with or without human intervention. The task is considered complex because several interacting variables must be considered to make appropriate decisions. The high level of time pressure also adds complexity to the task: time taken to make a decision or to gather more information necessarily comes with a cost since the fire continuously grows with the passing of time.

The fire model in the simulation is based upon actual research on forest fires [58]. This microworld is designed to include important characteristics of a real fire-fighting system and has controls that allow researchers to adjust the complexity of the task and manipulate its cognitive demands.

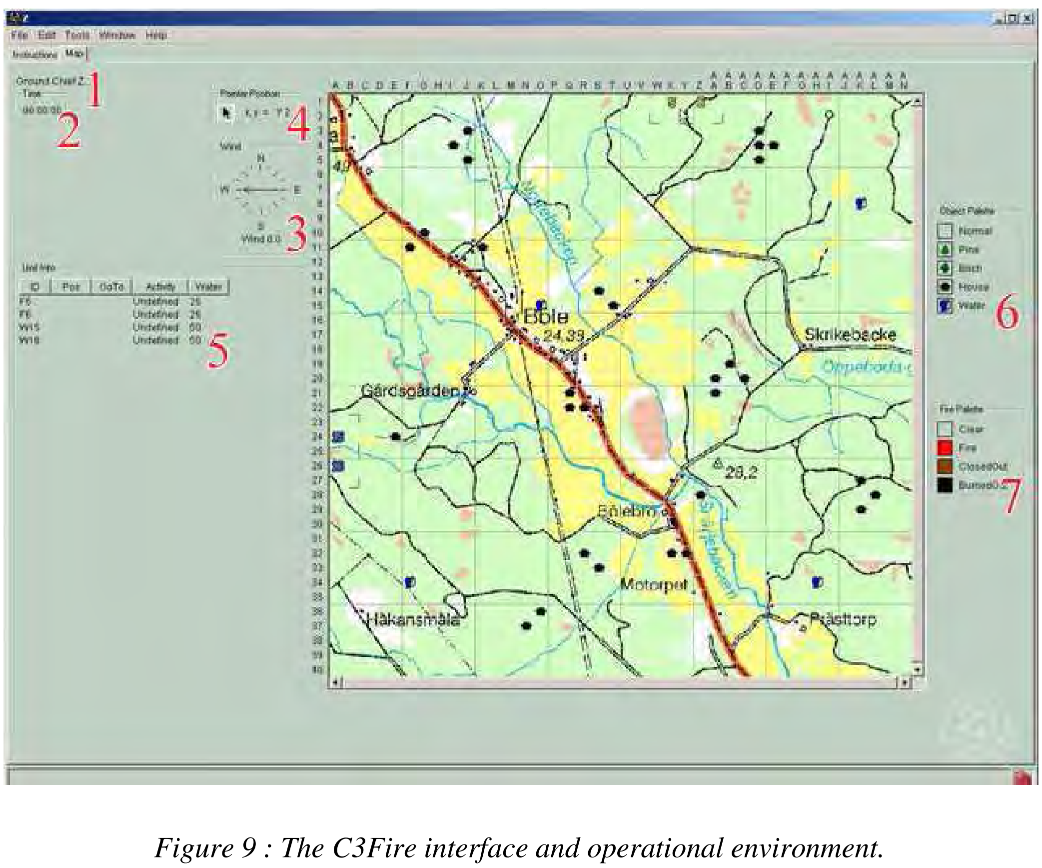


Figure 9 : The C3Fire interface and operational environment.

The simulation takes place in a 40x40 matrix, representing a geographic map seen from a bird's eye view. Figure 9 shows the different parts of the interface and of the operational environment. The red numbers mark distinct information panels: 1) the role of the player, 2) game time, 3) the wind panel, 4) pointer coordinates, 5) the unit information panel, 6) the fire palette, and 7) the object palette. The fire palette and the object palette act as a legend for the icons and color on the map. Units are identified by a blue or yellow number on the map. Blue units correspond to water tankers and yellow units represent firefighters.

The C3Fire microworld is built up with a set of four interacting simulation layers: 1) a fire layer, 2) a geographical objects layer, 3) a weather layer and 4) a unit layer.

Fire layer. The fire layer concerns the state of an area which is represented by a color code. Cells may be red (on fire), black (burned out) brown (closed out) or clear. A fire panel located on the right of the map indicates the possible area states to the participants (see Figure 9).

Geographical objects layer. Four types of geographical objects are differentiated in the C3Fire microworld: houses, lakes, pines and birches. Different objects may be set to ignite faster or slower than normal cells. An object panel, located on the right of the map, lists the different types of objects to the participants.

Weather layer. The weather layer is represented by the force and the direction of the wind. As the wind speed increases, the fire spreads faster in the direction the wind blows and spreads slower in the opposite direction. The wind panel, located at the upper right of the map, indicates wind strength and direction to the participants.

Unit layer. The unit layer in C3Fire comprises three different types of units: firefighters, water tankers and reconnaissance units. The firefighters combat fire, water tankers refill firefighters, and reconnaissance units scan the map to discover new fires. Each unit is represented by a unique identification number. An arbitrary number of units can be set to appear in a given C3Fire scenario. Each unit awaits orders from its predetermined commander. The unit information panel displays information on the units controlled by a participant. This panel displays a unit's identity, its current position, destination, current activity, and current available water cells.

A participant must left-click on a unit drag the unit's "movement intention icon" to another area in order to order it to go to that destination. Figure 10 shows that when a unit is moving, its number or icon appears in blue within the destination square.

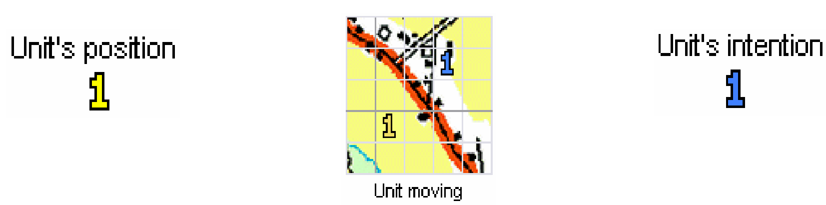


Figure 10: Moving units. Representation of position and destination.

The main goal of the task is to limit the fire's progression by extinguishing cells that are on fire as quickly as possible before the fire spreads to adjacent areas. To do so, a firefighter must be positioned directly over a burning cell. After a preset amount of time, burning cells completely

burn out and turn black: they are considered “lost”. If a firefighter succeed in extinguishing a cell before it burns out, then it turns brown and is considered “saved”. The time required to close-out a burning cell is set by the experimenter, like the time required to mobilize when arriving on a new fire and the time to demobilize once the fire is out. A firefighter needs a certain amount of water to extinguish a fire and the water is spent at a certain rate. To refill a firefighter, a water tanker must be placed beside the firefighter. When a water tanker has spent all his water, it needs to refill its water supply next to a lake. The refill process takes place at a predetermined speed. The time needed for a unit to move from one cell to another can also be set by the experimenter. These key parameters of the simulation can be adjusted to produce varying levels of time pressure thus reducing or increasing task difficulty.

Additional goals may be set to make the task more complex and realistic. For instance, protecting houses can be considered a priority. Also, if participants do not automatically see new fires on the map (an optional setting), then another important goal is to use reconnaissance units to locate fires in the operational environment. Other extensions include fire-breaker units (used to block fire progression), swamp terrain (that cannot burn), schools (high priority objects), and fuel logistics.

Participants perform the task on individual work stations. To exchange information, they must communicate using headphones with integrated microphones. The key challenges in C3Fire are to locate the fires, to select the most important fires to extinguish first, to ensure that firefighters are refilled in a timely manner, and to re-supply water tankers at appropriate times. These micro-decisions form an implicit or explicit strategy for attaining both proximal and distal goals.

Despite some lack in the “face validity” of C3Fire for simulating tactical C2, it is clear that this microworld reproduces many of its critical aspects and provides a challenging arena for team decision making:

> “One of the most important advantages is that the C3Fire environment creates a large motivational appeal and that user acceptance has been high with the professional subjects at the Swedish National Defence College. The professional subjects quickly adopted analogies to their own field of expertise, and they also often used their professional ‘‘language’’ when interacting. This, and the fact that many of the teams clearly stated that they found the simulation valuable, indicates that the microworld, even though the simulation is fairly simple, reflects some of the crucial aspects of team work in dynamic settings” [60].

3 Performance analysis

This section presents the data-driven component of the methodology for estimating the costs/benefits of teamwork: data collection and performance analysis of different team structures. Below, we describe the objectives of the study, the method of the experiment and results of the data analysis. We complete the analysis by comparing two multiple regression models that show key similarities and differences in the functioning of the two team structures that were tested.

3.1 Objectives

C2 teams can be organized in different ways to better match the requirements of various tasks and conditions [65]. One challenge for team research is to determine the set of key factors that contribute to team performance, partly because these factors vary according to the context [66]. Within a same task context, it is unclear whether factors of team performance vary as a function of the organizational structure of the team. The key objectives of the experiment reported here are:

1. To measure the effectiveness of different team structures in a dynamic C2 task

2. To assess differences in team functioning as a function of team structure.

The C3Fire microworld provided the experimental testbed for studying C2 in a team environment. C3Fire is a dynamic system, where fires evolve in real time, both autonomously and as a consequence of the team's decisions and actions. The goal of each team was to extinguish a maximal number of fires while attempting to save constructions in the neighbourhood.

3.1.1 Team structures

The experiment studied the effectiveness of three-person teams as a function of team structure. There were two possible roles in the current C3Fire experiment: firefighting and water-provisioning. Each team member was either specialized in one role or performed both roles, depending on the team structure. The assignment of roles/units to each team member was either functional (role-specific) or multifunctional (ranging over multiple team functions).

In the multifunctional structure, each participant controls a subset of firefighters and water tankers. Each participant is thus capable of working relatively independently. In the functional structure each team member fulfills a specific role. Team members are highly interdependent and must work together to accomplish the task. The key difference between these two structures lies in their respective coordination requirements. Table 2 shows the specific allocation of units to each team member as a function of team structure. Note that the total team resources (firefighter units and water tankers) are the same for both structures. Any differences between team structures in terms of effectiveness or observed team processes (i.e., communication, coordination, etc.) should therefore be attributable to the impact of team structure.

Table 2: Unit allocation for the three participants according to team structure.

Structure	Unit allocation
STRUCTURE 1 Multifunctional	Agent X: Firefighters = 2, Water tankers = 2 Agent Y: Firefighters = 2, Water tankers = 2 Agent Z: Firefighters = 2, Water tankers = 2
STRUCTURE 2 Functional	Agent X: Water tankers = 6 Agent Y: Firefighters = 3 Agent Z: Firefighters = 3

3.1.2 Critical changes

Teams performing in command and control environments are often faced with sudden and unexpected events that can modify the pace and demands of the situation to a great extent. To function effectively, these teams must adapt to such transitions and be efficient in coordinating their actions. The experiment was therefore designed to investigate how teams respond to critical events in C3Fire. Each scenario began with a fire at the map's center. Two types of events could dramatically influence the spread of the fire: a change in the strength and direction of the wind and the ignition of a new fire elsewhere on the map. Participants had to detect these changes, communicate them to their team members, and adjust their behavior in consequence.

3.2 Method

3.2.1 Participants

Twenty-four 3-person teams performed a 2-hour experiment including 2 practice and 4 test scenarios (15 min each). Participants were recruited from the student population at Université Laval. They received a 15$ compensation for participating in the experiment. Teams were randomly assigned to a multifunctional or functional organizational structure. Figure 11 summarizes the unit (and role) allocation in each team structure.

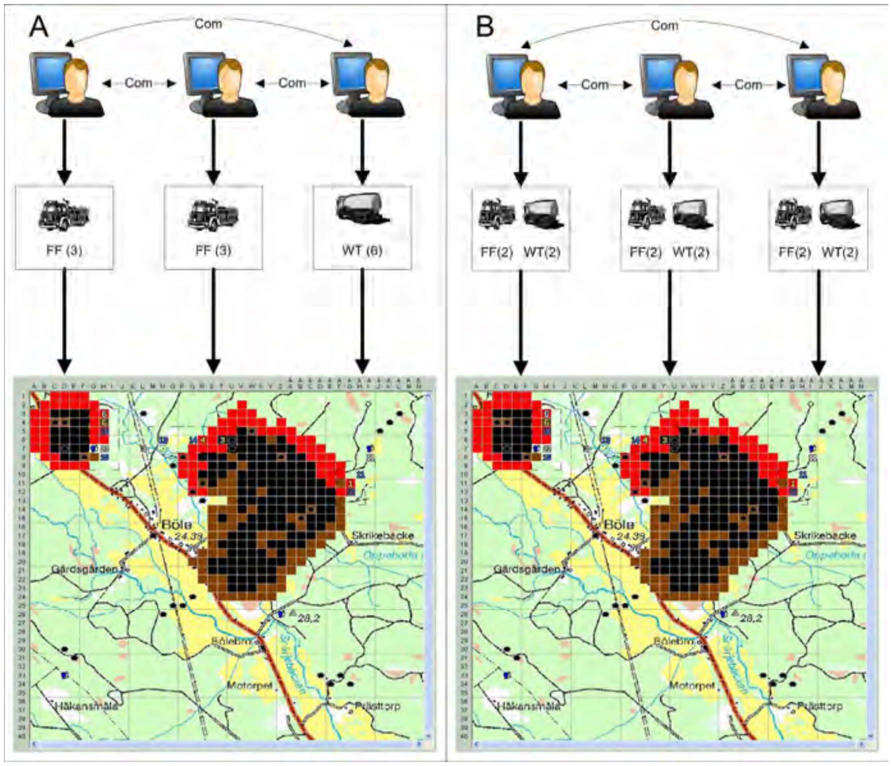


Figure 11: Functional structure (left side): Each team member controls only one type of unit. Roles are specialized and interdependent. Multifunctional structure (right side): Each team member controls a subset of each unit type, allowing them to operate independently in their joint effort.

Participants were instructed to manage multiple goals in C3Fire, ordered by priority:

3. To prevent houses from igniting

4. To limit the spread of the fire

To extinguish burning houses

3.2.2 Material

The experimental took place in a University laboratory with four networked computers using 3 programs: C3Fire, Team Speak and Morae. TeamSpeak software allowed communication between team members; they communicated via headsets by holding down the zero key on the numeric pad. Participants could give orders to their units using the mouse. During scenarios, every event that happened in the microworld (e.g., keystrokes), as well as continuous screen captures and communications between participants were recorded using Morae software (TechSmith).

3.2.3 Scenarios

Seven scenarios were designed for the present study. A 10 min scenario was developed for a basic familiarization with the interface and commands. Two 10 min scenarios served as practice trials to ensure that participants were proficient in their role(s). Four 15 min test scenarios were used to study team performance. Two critical changes occurred during the course of each test scenario. At each critical change, either a new fire started somewhere on the map or the wind increased and changed direction.

Table 3: Critical changes in C3Fire for each test scenario.

	Critical change 1 (2:19)	**Critical change 2 (2:25)**
Test 1	Fire	Fire
Test 2	Fire	Wind
Test 3	Wind	Wind
Test 4	Wind	Fire

Note. Test scenarios began at 2:15 pm and finished at 2:30 pm (game time)

Thirty houses were placed in each test scenario at different positions. Twenty of these houses were positioned so as to burn out before the end of the scenario either due to the starting fire or due to the effects of a critical change. This ensured that it was indeed critical to take heed of these changes. Figure 12 illustrates a test scenario after two critical changes (two new fires).

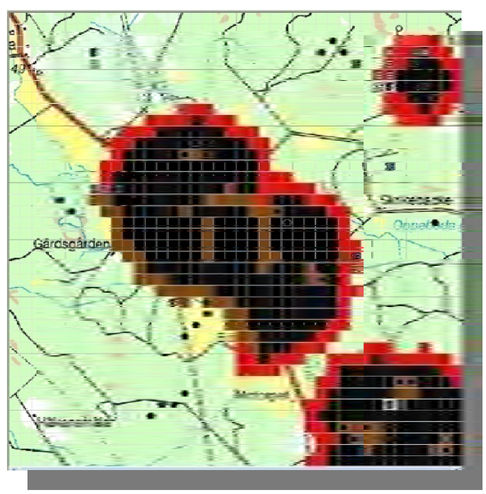


Figure 12: Example C3Fire scenario with two new fires.

3.2.4 Procedure

Participants were randomly assigned to a computer station (X, Y or Z) at their arrival in the research laboratory. They listened to instructions and followed directives from the experimenter during a familiarization session aimed at explaining the objectives and how to perform different actions in C3Fire. Two practice scenarios followed. The order of the four test scenarios was

counterbalanced across teams. At the end of the experiment participants completed a questionnaire asking them to rate their perceived workload on to dimensions: mental load and time-pressure. These two dimensions of workload are part of the NASA TLX workload rating scale [67]. Each dimension was rated on a scale from 1 (very low) to 10 (very high).

3.2.5 Measures

The independent variable which was manipulated in the present experiment is team structure. The effect of team structure was assessed on five dependent variables:

5. Performance (combination of houses saved and closed out cells)

6. Coordination (total time firefighters spent without water)

7. Communication frequency and classification

8. Monitoring effectiveness (latency to detect critical changes)

9. Perceived workload (mental load & time pressure)

Performance in C3Fire is defined by the team's success in managing both the *defensive* and the *offensive* aspects of the task, namely protecting the houses from the fire and closing out at many fire cells as possible. Performance is calculated by multiplying the proportion of saved houses by the number of closed out cells. Higher values correspond to a better overall performance. The proportion of saved houses corresponds to 20 (the number of houses that are set to burn out if participants do nothing) minus the number of houses which are burned out at the end of a scenario, divided by 20:

Performance = number of closed out cells X (number of houses saved/20)

Coordination is measured by the total time each firefighter (FF) spent without water. Lower values correspond to a better coordination. This measure specifically refers to *resource-oriented coordination*. This type of coordination refers to process that serve primarily to manage dependencies between activities or resources dependencies [68]. It provides an excellent indication of the efficiency in performing the water refill process, which requires coordination between water tankers (WT) and FF. A second important type of coordination not measured in the present experiment is goal-oriented coordination. Goal-oriented coordination is when participants make decisions about priorities or develop strategies on how to fight the fire or protect houses.

Communication frequency refers to the total number of messages sent by each team member to his teammates. These communications were first categorized into seven communication topics: Fire, houses, wind, actions, units, positions, and water. These topics were then regrouped into those related to resource-oriented coordination (units, positions and water) and those related to goal-oriented coordination (fire, houses, wind, actions). This allowed a comparison of the proportion of communications related to each type of coordination.

Monitoring effectiveness is defined as the latency to detect critical changes. Participants are instructed to communicate to the others the fact that they have detected a new fire or a change in wind strength and direction. Monitoring effectiveness is obtained by calculating the time taken for one of the participants to notice the critical change and communicate this observation.

Perceived workload is measured only once at the end of the experiment. Participants are required to rate the overall mental load and time pressure that they personally experienced during the four test sessions. This measure can give both an average workload rating for each team, or allow a more detailed analysis of workload distribution according to the role(s) performed by different participants (firefighting, water provisioning, or both).

3.3 Results

For the following analyses, the measures of performance, coordination, communication and monitoring effectiveness each team, we first calculated the average results across the four test scenarios.

3.3.1 Performance

Team performance (closed out cells X proportion of houses saved) differed significantly between the multifunctional and functional structure, $t(22) = 2.92$, $p < .01$. Multifunctional teams obtained on average a better performance score (M = 49.36, SD = 12) than functional teams (M = 32.73, SD = 15.64). Table 4 presents the results of three comparisons done three distinct measures for functional and multifunctional teams. It decomposes the two element of the performance measure (the defensive and offensive aspects of the task) and shows that multifunctional team were significantly more effective at saving houses (M = 15.44, SD = 1.95) than functional team (M = 11.79, SD = 3.98). They were also significantly more effective at closing out as many fires as possible (M = 64.5, SD = 15.04) than functional ones (M = 52.31, SD = 11.46).

Table 4: Results of the t-tests comparing the two team structure when decomposing the two elements of team performance.

Measure	***T***	**Sig. (2-tailed)**
Houses saved (defensive)**	2,849	0,009
Closed out cells (offensive)*	2,233	0,036
Performance (global)**	2,921	0,008

* significant difference at p < .05
** significant difference at p < .01

3.3.2 Resource-oriented coordination

The total time FF units spent without water differed significantly as a function of team structure, $t(22) = -3.485$, $p < .01$. Time without water was higher for functional teams (M = 2374.17 sec, SD

= 598.81) compared to multifunctional teams (*M* = 1649.42 sec, *SD* = 393.49). Multifunctional teams were therefore better at coordinating FF and WT to satisfy resource (i.e., water) dependencies. We found a significant negative correlation between coordination effectiveness (lower being better) and team performance, $r(22) = -0{,}59$, $p < .01$.

3.3.3 Communication frequency and classification

The number of communications was significantly greater in functional teams (*M* = 121, SD = 37) comparer to multifunctional teams (*M* = 91, *SD* = 29.11), $t(22) = -2.219$, $p < .05$. The topics of these communications also differed in their proportions. Communications associated with resource-oriented coordination (units, positions and water) occurred proportionally more often in the functional teams than in multifunctional teams, $t(22) = -6.678$, $p < .01$. Communications associated with goal-oriented coordination (fire, houses, wind, actions) on the other hand, occurred proportionally more often in the multifunctional teams compared to functional teams $t(22) = 6.678$, $p < .01$. Since these two communication categories are mutually exclusive, the t-values of these two comparisons are the same (but with a different sign). Figure 13 shows the proportions of these two types of communication as a function of team structure.

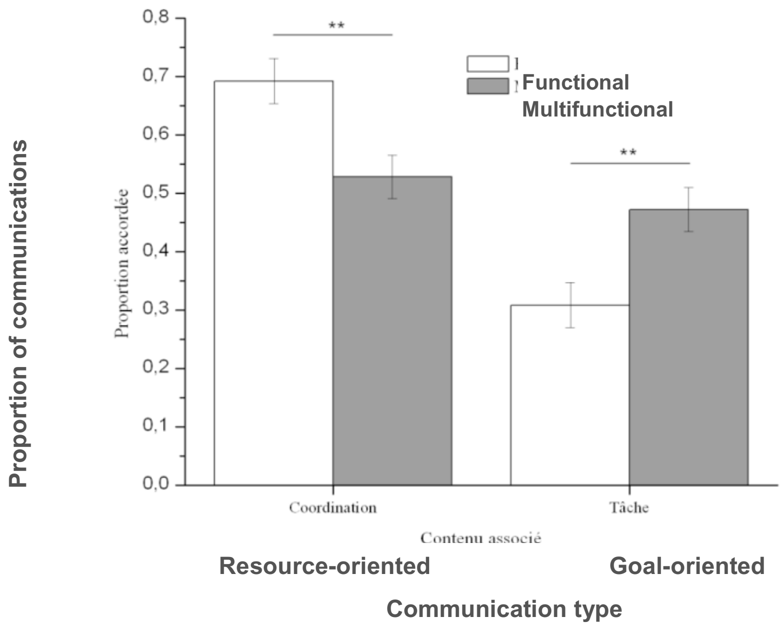


Figure 13: Proportion of each type of communication as a function of team structure.

3.3.4 Monitoring effectiveness

The average latency for detecting critical events, i.e, the time required for one of the team members to detect and communicate the occurrence of a critical change, did not differ significantly between the two team structures, $t(22) = -.199$, ns. No difference related to team structure was found when analyzing detection latency for the first critical change in a scenario, $t(22) = -1.227$, ns., nor the second one, $t(22) = 1.034$, ns.

3.3.5 Perceived workload

No significant difference between team structures was observed for subjective workload ratings, t(22) = -0,72, ns. Functional teams (*M* = 15,13, *SD* = 2,28) showed comparable average workload rating to those of the multifunctional teams (*M* = 14,50, *SD* = 2,04). However, workload distribution among the team members was not the same in the two organizational structures. We compared the perceived workload of Participant X_F (the one in the functional structure with 6 WT units) to the averaged perceived workload of Participant Y_F and Z_F, who each controlled 3 FF units. We performed the same comparison for Participant X_M (in the multifunctional structure) and the average workload rating of Participants Y_M and Z_M.

In the multifunctional structure, no difference was expected since all three participants control 2 FF and 2 WT units. Indeed, no significant difference in workload distribution was found in the multifunctional structure, $t(22) = .218$, ns. However, for the functional structure, the workload rating of Participant X_F was found to be significantly greater than that of his two teammates, $t(22) = 3.296$, $p < .01$. Workload was distributed unequally in the functional structure. The reason for not observing a global difference in the workload of the functional team structure compared to the multifunctional structure is explained by the fact that Participants Y_F and Z_F (who control 3 FF units) actually have on average lower workload ratings that participants in the multifunctional structure (who control a total of 4 units).

A statistically signification correlation was found between communication frequency and each of the two dimensions of workload that were measured. The higher the frequency of communications, the higher the mental load, $r(22) = .58$, $p < .01$ and time pressure, $r(22) = .481$, $p < .05$.

3.4 Discussion

The experimental results show that team structure had an important impact on team performance. A greater team performance was observed in the multifunctional structure. Multifunctional teams were better at resource-oriented coordination and communicated less frequently. These results are in line with key finding from Stammers and Hallam [69] suggesting that team structures need to minimize the need for interpersonal coordination in order to be more efficient. However, another key finding in the literature seems to contradict the above results. Functional teams tend to be more effective than multifunctional teams in situations that are routine and predictable [50].

Multifunctional teams have the potential benefits of minimizing the interdependence between team members and requiring little communication, but they require managing different types of functions and therefore may require more information and involve task switching costs. In a functional structure, team members may benefit from task specialization: the information requirements are reduced and there is a reduced task switching cost. However, interpersonal coordination is considerably more demanding in situations that are more dynamic and less predictable and functional teams are penalized under these conditions (as observed here and in [70]).

Our analysis suggests that there is an apparent trade-off between the costs of interpersonal coordination and the benefits of task specialization in functional teams. This trade-off can be

either beneficial or detrimental to functional teams depending on whether the task is repetitive and predictable or not [71]. Functional teams are more effective than multifunctional teams in predictable situations because interpersonal coordination can be achieved simply by relying on routine procedures (i.e., planned coordination that requires little communication). However, interpersonal coordination is considerably more demanding in situations that involve constant change and are less predictable. Functional teams are therefore penalized under these conditions because they require more interpersonal coordination than multifunctional teams. In light of the trade-off discussed above, it is clear that C2 teams should therefore adopt a structure that matches the requirements of their actual task and operating conditions.

Two additional factors may further explain the relatively lower performance of functional teams observed in our experiment: *workload imbalance* and *task dependency*. First, while there was no significant difference in the overall workload of functional and multifunctional teams, there was a *workload imbalance* among members of functional teams. Participant X_F, in charge of controlling all six water-tankers, generally reported having a higher workload than Participants Y_F and Z_F, who were each in charge of 3 firefighters. This result can be easily explained by the fact that a distribution of 4/4/4 units in the multifunctional structure may produce a more balanced workload than a distribution of 6/3/3 units. It is therefore possible that functional teams were disadvantaged compared to the multifunctional teams in part because Participant X_F was overloaded. Second, functional teams are characterized by *interpersonal task dependency*. A functional task allocation tends to make some team members depend on others due to task dependency. In the case of C3Fire, Participants Y_F and Z_F need water from Participant X_F to perform their task correctly, so overloading Participant X_F can be very detriment to overall team performance.

One challenge for team research is to determine the set of key factors that contribute to team performance [12]. However, can we assume that these factors are constant for different team structures? In the present study, did factors of team performance vary as a function of the structure of the team? As a final analysis, we addressed this issue by deriving two multiple regression models from the data, one for each team structure. The predictors of performance included in the analysis were coordination efficiency, communication frequency, monitoring effectiveness and two subjective workload measures (time pressure and mental load).

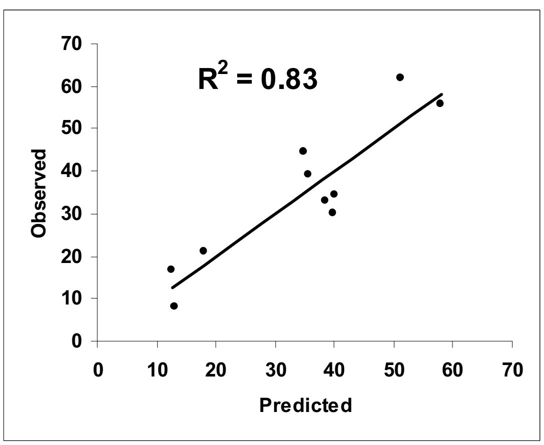
We found that monitoring effectiveness was not a useful predictor of team performance and we removed this factor from the regression models. This variable provided no gain in explained variance in both regression models. We assessed the importance of the other factors selected for the regression models by computing the decrease in proportion of variance explained by the regression models when that variable is excluded. Table 5 shows the results of this test showing that each variable is worth keeping.

Table 5: Relative importance of different factors for the two regression models defined by loss of explained variance when excluding that factor.

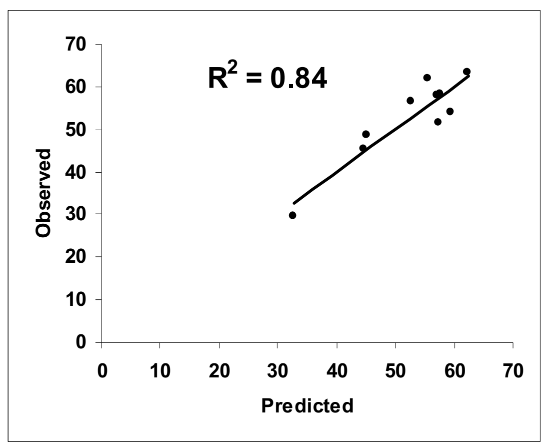
	Team structure	
Predictor variable eliminated	**Multifunctional**	**Functional**
Resource-oriented coordination (time without water)	-0.28	-0.27
Communication frequency	-0.22	-0.31
Mental load	-0.07	-0.11
Time pressure	-0.09	-0.00

Note.The higher the reduction in proportion of variance explained, the greater the importance of that factor.

Both models provided excellent fits to the data. The regression model for multifunctional teams accounted for 84% of the variance in team performance. The second regression model accounted for 83% of the variance in the performance of functional teams. Figure 14 presents the scatter plots for observed and predicted performance for each regression model.



Functional teams



Multifunctional teams

Figure 14: Scatterplots for observed and predicted performance for each regression model.

Table 6 shows the standardized coefficients for each regression model.

Table 6: Standardized regression coefficients for the multifunctional and functional team structure.

	Team structure	
Predictor variables	**Multifunctional**	**Functional**
Resource-oriented coordination (time without water)	-0.82	-0.61
Communication frequency	-0.75	0.69
Mental load	0.35	-0.66
Time pressure	0.37	0.13

The regression coefficients showed similarities and differences in the predictors of team performance across team structures. There are two main results. First, coordination was important in both team structures for predicting performance. Both models associate a better (lower) resource-oriented coordination to an increase in performance. Second, communication frequency was positively related to performance in the functional structure whilst negatively related to performance in the multifunctional structure. This result suggests that communication requirements change as a function of team structure. Indeed, in functional teams, more communications came with a better performance (communicating was essential in this structure), whereas in multifunctional teams more communications came with a lower performance. The regression coefficients for mental load and time pressure are somewhat surprising. It was expected that higher perceived workload would lead to a reduced performance. This was only the case for mental load in the functional team structure. We suggest that the relation between workload and performance may be non-linear and have real detrimental effects only when participants are overloaded. This issue will require further investigation.

The above findings suggest that teamwork requirements and the importance of various team factors in general may vary as a function of team structure. This novel result has important implications. For instance, future research should no longer attempt to identify a general model of team performance that uses team processes as predictor variables because the role of these processes is not the same from one team structure to another.

4 Task analysis

The C3Fire microworld has provided an experimental testbed for studying dynamic decision making and teamwork in socio-technical systems. The experiment reported in Section 3 collected data that will provide key constraints for estimating the costs/benefits of team structures. When attempting to model a complex phenomenon, it is the constraints imposed by observed facts and theoretical knowledge that give meaning to the analysis: "*There are so many possible models that the main problem is not usually how to construct a model, but how to constrain the myriad possibilities down to something useful*" [72]. Since the main difference between team structures is task allocation, it is essential to carry out some form of task modeling to identify the set of subtasks that can be allocated to different participants. The task analysis presented in this section thus provides an important set of constraints for the ulterior development of an analytical method aimed at estimating the cost/benefits of different team structures. This is the task-driven component of our methodology.

4.1 Objectives

The main goal of the current analysis is to identify and document the subtasks that must be performed to successfully operate in the C3Fire microworld. This analysis does not focus on a particular team structure: it represents the generic tasks that must be performed regardless of the actual assignment of units and subtasks, either to a single agent or to several team members.

HTA [61; 62; 63; 64] is selected as the method of task analysis because it is a widely used, generic approach that is also the basis of a number of more specialized methods. HTA has the benefits of being readily understandable and provides few constraints on the analysis. A hierarchical structure is a central component of most approaches to task analysis and task modeling.

> "HTA is a core ergonomics approach with a pedigree of over 30 years continuous use. […] HTA has endured as a way of representing a system sub-goal hierarchy for extended analysis. It has been used for a range of applications, including interface design and evaluation, allocation of function, job aid design, error prediction, and workload assessment" [64].

In the present endeavour, HTA is used to obtain a detailed view of the C3Fire subtasks in order to characterize the total *workload* associated to this task (also referred to as taskload).

4.2 Method

4.2.1 HTA

HTA is focused on goal description and decomposition. Subtasks are viewed as subgoals required to achieve a higher-level goal. A goal can be active or latent. An active goal is pursued intentionally throughout task execution. A latent goal can become active at a specific moment during task execution when certain conditions arise. HTA mainly consists of decomposing a main task into a hierarchically organized set of subtasks. Links between different subtasks can be formalized as plans. The main task can be decomposed in as many levels as needed, depending on the degree of specificity desired. One possible aim of the analysis is “to identify actual or possible sources of performance failure and propose suitable remedies” [73]. Here, we use HTA specifically for task description. Our analysis does not require formalized plans.

Annett [73] defines seven steps in HTA. The first step is to clearly define the goal of the analysis, since it influences how data gathering will be done and also has an impact on the solutions which can be applied. More importantly, the goal of the analysis determines the depth of the analysis, that is the moment when enough information is available and no further decomposition is needed.

The second step in HTA is to arrive at a consensus between all the persons concerned by the task on what the performance goal is. Therefore, a discussion with all the stakeholders is needed to ensure that a same view of the task is shared, and to identify differences in plans (ways to attain the goal) that may occur between them. During this step, it is also important to define the precise criteria of goal achievement.

The third step consists of identifying which sources of information will be used to perform the HTA. Those sources may vary according to the use of the analysis. The means that are most frequently used are interviews with experts which can be general or focused, direct observation, formal performance records like flight recorders, and experimental trials or simulations. In the absence of any performance data, hypothetical questions are formulated which will help estimate what is at stake.

The fourth step involves drawing the HTA diagram and/or HTA table, using the information obtained in step 3. Diagrams tend to provide a global perspective and are easily understood, while tables can be easier to follow when the analysis has a very large number of elements and takes multiple pages. Tasks are assigned numbers that identify their position in the hierarchy. The number 0 is always attributed top-level task and numerals are assigned to each primary goal. A digit is then added for each new level of decomposition. Suboperations must be mutually exclusive and exhaustive in order to define the superordinate operation [73]. Figure 15 shows an example of an HTA diagram for making a cup of tea. Figure 16 shows an example in tabular format for a chemical incident.

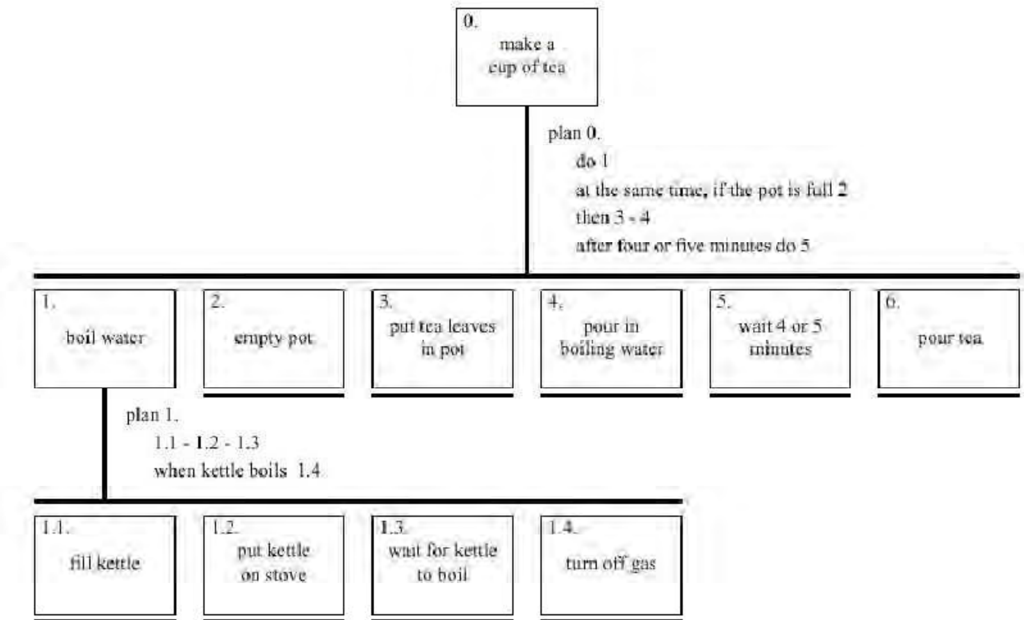


Figure 15: HTA diagram for making a cup of tea (from [74]).

0. Deal with chemical incident
Plan 0: Wait until 1 then do 2 then 3-If [hazard] then 4 then 5 then exit -
Else exit
1. [Police control] receive notice from public about incident //
 2. [Police Control] gather information about incident
 Plan 2: Do 2.1 at any time if appropriate
 Do 2.2 then 2.3
 Then exit
 2.1. [Hospital] inform police control of casualty
 with respiratory problems//
 2.2. [Police Control] get a Police Officer to search
 scene of incident
 Plan 2.2: D o 2.1.1 then 2.2.2 then 2.2.3
Until [suspects] or [hazards] then exit
 2.2.1. [Police Control]
 Send Police Officer to scene of incident//
 2.2.2. [Police Officer] arrive at scene of incident//
 2.2.3. [Police Officer]search scene of incident//
 2.3. [Police Control] get Police Officer to report nature of incident
 Plan 2.3: If [suspects] then
 2.3.1 If[suspects] then 2.3.2. then 2.3.3
 Then 2.3.4. then exit Else exit
 2.3.1. [Police Officer] identify possible hazard//
 2.3.2. [Police Officer]capture suspects//
 2.3.3. [Police Officer] gathe r information from suspec ts//
 2.3.4. [Police Officer] inform police control of nature of incident//
3. [Police Control] make decision about nature of incident//
4. [Fire Control] clean up chemical spillage
etc...
5. etc...

Figure 16: Example of HTA in tabular form [64].

The fifth step in an HTA consists in cross-checking the validity of the analysis. The analysis should be shown to and discussed with the stakeholders. Cross-checking the validity of the results can also be accomplished by using sources such as training manuals and interviews with operators. This step helps identify missing subtasks and errors. This stage of HTA development tests the internal validity of the proposed task decomposition.

The sixth step is to identify the degree of precision needed in relation to the purpose of the analysis. If the purpose of the analysis is to search for sources of performance failure, it can be decided to stop the analysis when it is not possible to find further error sources. However, if its purpose is to define a specific task, the analysis can be stopped when the level of detail is sufficient to provide a good view of the task. In this analysis, the purpose was to clearly define the set of subtasks in the C3Fire microworld.

The seventh and last step consists of generating test hypotheses, that is, to invent situations that would be likely to occur and propose solutions to those situations. This stage is basically a form of external validation.

Though all these steps were not required for the purposes of the present analysis, they have served as a guide for selecting the appropriate steps for task decomposition. HTA is a simple and effective method for task decomposition widely used in North America and the UK. The major advantage of this approach over other forms of task analysis is that its simplicity makes it accessible to non-specialists.

4.2.2 Procedure

The present analysis was accomplished by two undergraduate students having acquired extensive experience with the C3Fire microworld, a doctoral student familiar with basic and applied research methods and a human factor specialist with expertise in cognitive modeling and task analysis. The HTA of the task simulated in the C3Fire microworld relied on three information sources: 1) existing documentation, 2) observation, and 3) SME interviews. These are the three primary sources of information generally used for performing an HTA [75]. A unique feature of the present hierarchical task analysis is that the two student-analysts that were also trained as subject-matter experts (SME). The two university students thus performed mutual observation and cross-interviews in order to identify the different subtasks by taking in turn either the role of an HTA analyst or of an SME.

The students gained expertise about C3Fire by repeatedly playing the game during several weeks in the midst of a scenario calibration phase prior to experimenting. Before the analysis, the students did an in-depth learning of C3Fire's functioning and of the configuration of its various parameters. They consulted the C3Fire website in order to become well-acquainted with the features and mechanics of the microworld. Additionally, they consulted selected scientific papers to acquire sufficient knowledge of command and control, dynamic decision making and hierarchical task analysis.

In an initial stage of the analysis, two versions of the task decomposition were independently sketched and then put together by the subject-matter experts. The SME-analysts decomposed the game's actions by recalling them from memory and consulting documentation on command and control (to stay in line with the general purpose of C3Fire as a functional simulation of C2). Next,

the analysts collaboratively identified and organized subtasks into a coherent hierarchy during an iterative development process. The first draft was then computerized using Mindjet MindManager Pro 6. Meetings with the doctoral student and human factor specialist helped identify ways to improve the precision and internal coherence of the task decomposition.

A second stage of the task analysis was to validate it using replays. Scenarios were recorded using Morae Recorder software version 2.0.1. These recordings allowed a session to be captured on video and replayed at will. For the present analysis, two distinct scenarios have been captured in this way. The first scenario was played twice by the SME-analysts in order to allow them to switch roles. Scenario 1 used a functional team structure where firefighters are controlled by an agent and water tankers are controlled by the other agent. A functional team structure was selected because it requires more coordination work across agents, making some processes more easily observable through communications. During the first session, one expert controlled the firefighters and the other controlled water tankers. The roles were then reversed for the second session.

Scenario 2 familiarized the analysts with the subtasks associated to reconnaissance units. One reconnaissance unit, two firefighters and two water tankers were assigned to each agent in a divisional team configuration. Each expert was instructed to operate within the left or right half of the map which was divided in the middle by a vertical blue line. Replays of Scenario 1 provided data on which to validate the initial task analysis. The validation was performed by a cross-observation of the replays by the two SME-analysts. The first expert observed the second expert's replay and vice-versa. Scenario 2 helped incorporate the subtasks associated with reconnaissance units, which had not been included in the original analysis. One scenario was sufficient to perform a satisfactory task decomposition related to commanding reconnaissance units. No further sessions were deemed necessary since the key features of the reconnaissance task had been successfully identified. The updated version of the analysis was then revised and completed in a final meeting with the supervising analysts.

Prior to showing results from the HTA, we describe an additional analysis performed to extend the description of the workload associated with the task simulated in C3Fire.

4.2.3 HTA extension

Although HTA can provide a detailed assessment of the various subgoals associated with a task, other more integrative (and complex) approaches can be useful to describe the work context more fully. One of these is the Groupware Task Analysis (GTA) framework, which aims to combine approaches from both human-computer interaction (HCI) and computer-supported collaborative work (CSCW) design [76]. According to this approach, analyzing a complex system requires characterizing the context across multiple dimensions:

10. the users;

11. the tasks;

12. the equipment (hardware, software, and materials);

13. the social environment;

14. the physical environment.

GTA describes complex task environments by focusing on agents, work, and situation elements [77]:

15. Agents and roles. Description of the active entities in the task world including users and stakeholders, systems and organizations. The roles and the organization of work (i.e. structure of agents and roles) need to be specified as well. Agents can be characterized on relevant characteristics such as knowledge, expertise, psychological traits, etc.

16. Work. The decomposition of tasks, the goals, the events that trigger the tasks, and the different strategies used to perform them.

17. Situation. Objects used in the task world as well as their structure. History of past relevant events, and the whole social and physical work environment. Objects may be physical or conceptual (e.g., messages, gestures, etc.).

Figure 17 illustrates the GTA ontology.

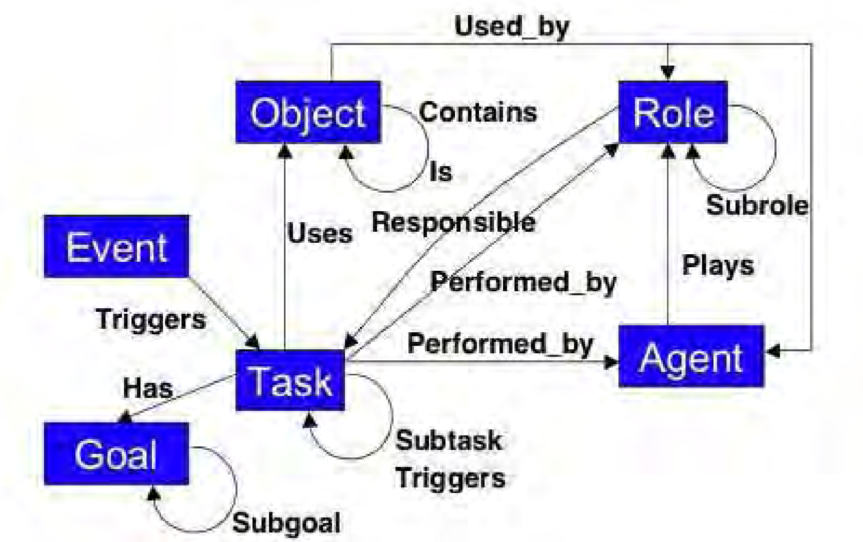


Figure 17: Ontology of Groupware Task Analysis.

The GTA framework was not chosen in the present study as a method for modeling both the task and the social context because the approach is currently not sufficient to model teamwork processes: “One of the aspects most difficult to represent with GTA was the differences due to geographical distribution and the transfer of information between different types of users” [77]. Nonetheless, the GTA approach has helped us identify useful elements to further characterize the subtasks identified in the HTA:

- *Information* requirements to accomplish the goal
- *Tools* needed to access information and perform actions
- *Events* that trigger the goal

- *Actions* required to accomplish the goal

Furthermore, we draw from the GTA ontology the key notion of *roles*. The different roles identified in C3Fire experiment are firefighting, water-provisioning and reconnaissance. How these roles are distributed across team-members will be central to our characterization and modeling of team structure in Section 6.

4.3 Results

Figure 18 presents the C3Fire task decomposition in the form of an HTA diagram. Next, we describe and discuss the key elements identified in the hierarchical task analysis and its extension based on elements from the GTA framework.

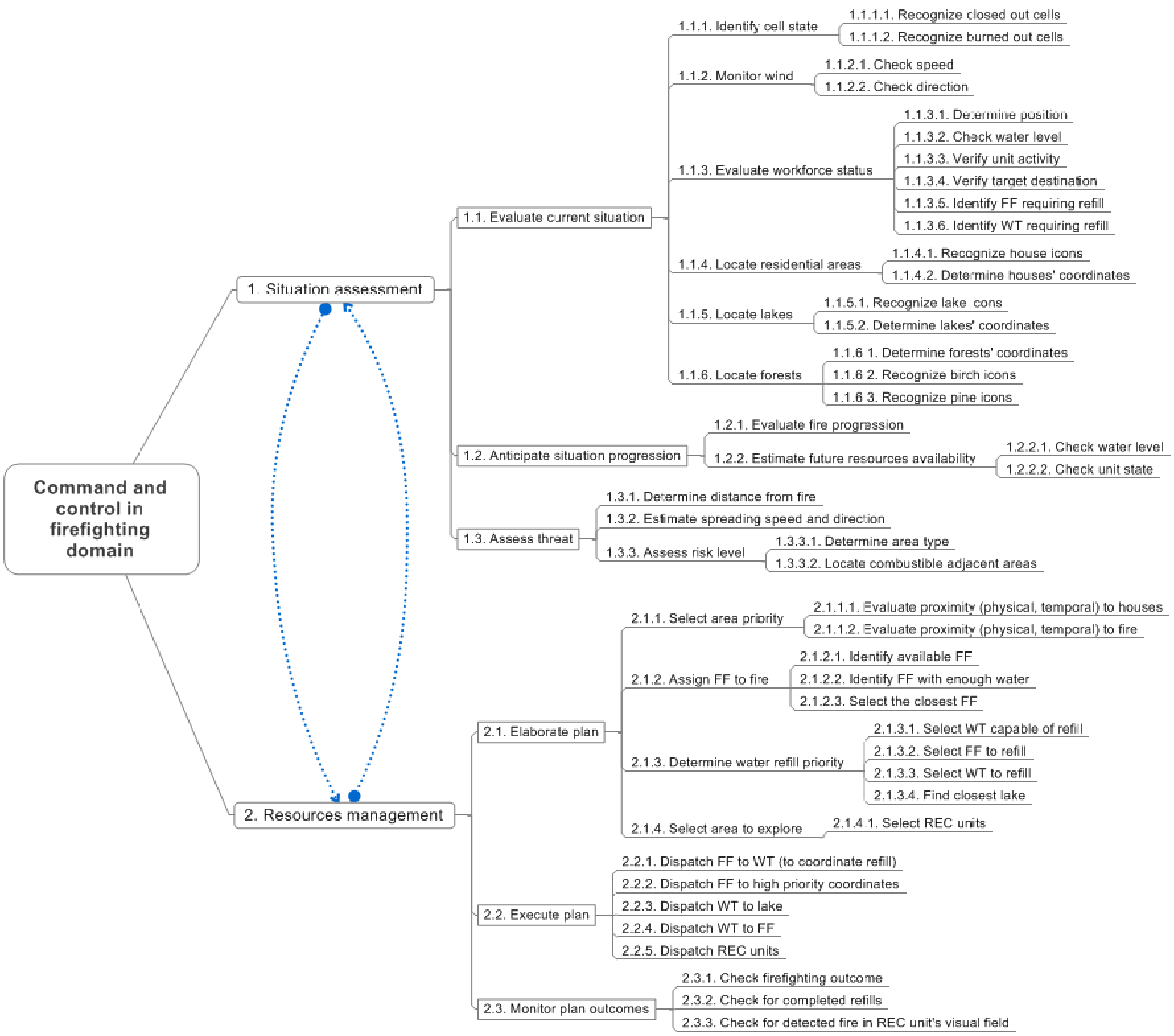


Figure 18: Hierarchical task analysis of C3Fire.

The task decomposition starts with a top level that describes the purpose of the C3Fire microworld, which is to simulate command and control in a firefighting domain. The general objective in terms of performance in C3Fire consists of controlling the spread of the fire and saving houses. To do so, the primary task of the players is to command their units and monitor their activities, that is, to perform command and control. For the purposes of the task analysis, this main task is divided in two subtasks: situation assessment and resource management.

4.3.1 Situation assessment

Situation assessment refers to having a global view of what is going on in the microworld and what may happen in the future. This process must be performed continuously during the execution of the task. Situation assessment can be divided into three subtasks: 1) evaluate the current situation, 2) anticipate the situation's progression and 3) assess threat. Evaluating the current situation is the primary subtask of situation assessment. It refers to forming a global image of the operational environment, by knowing where the important elements are located and in which state they are at the present moment.

The evaluation of the current situation is divided into many subtasks related to cells, units, weather and environmental elements. These subtasks are basically performed in parallel and do not follow a sequential order. The first one, identify cell state, consists of determining which cells are on fire, which cells have been closed out and which cells have burnt out. This will be useful later to establish priorities. The second task is to monitor the wind. This means being constantly aware of the current force and direction of the wind. Evaluate workforce status includes knowing the position of the units in the microworld, their water supply, their current activity, and, if they are moving, their current destination. The last three tasks refer to the location of the environmental elements which are the lakes, the forests and the houses. For lakes, it is relevant to know the proximity to water tankers. For houses, it is relevant to know the proximity to fire cells. For forests it is relevant to know the type of trees (pines or birches) it contains.

In the subtask of anticipating the situation's progression, the current knowledge of the situation is used to extrapolate what the situation will be in the future. More precisely, it is possible to anticipate which areas will be burning and which units will need water. Furthermore, it is possible to anticipate future unit states such as when units will become inactive (i.e., finish demobilizing), when they will be completely refilled, or when they will arrive at a target destination.

The last part of situation assessment is to assess threat, which means being aware of the imminence of fire reaching areas and weighting the threat according to the area type. This means integrating knowledge of how far this area is from the fire, how fast the fire is spreading towards it, which type of cells are around the area and if they are combustible or not. Overall situation assessment thus gives a global idea of what is going on within the microworld and provides information essential to the decision making process.

4.3.2 Resource management

Resource management refers mainly to choosing what to do with each unit as the situation evolves through time. It basically refers to decision making and planning. Resource management

is divided into three subtasks, all related to the notion of planning: 1) elaborate plan, 2) execute plan and 3) monitor plan outcomes.

Elaborating the plan consists mainly in making choices about what fires to fight, what units to send, which units to refill first, etc. Elaborating a plan is decomposed into three subtasks: 1) select area of priority, 2) determine water refill priority and 3) select area to explore. Selecting the area of priority consists in choosing which fire to extinguish first and which unit to dispatch. These choices a based on the information acquired through situation assessment. Potential firefighters must be available (not firefighting), they must have sufficient water to extinguish a fire, and they must be within a certain range to be able to extinguish the fire in time. Determining water refill priorities means looking for firefighters that need water and selecting an appropriate water tanker to refill them. The water refill process also involves deciding when a water tanker must be re-supplied in water and selecting a lake in the vicinity. Once more, situational information is essential to know which units need water, their position, and the location the nearest lake. Finally, selecting an area to explore is important in situations where reconnaissance units are available in the scenario and fires are not automatically visible on the map. A reconnaissance unit must be selected and a dispatch area must be chosen. The role of this unit consists in moving around the map and identifying fires within their limited visual range.

The execution of the plan is tightly linked to the elaboration of the plan. It is decomposed into five actions, which all refer to actually sending units to a chosen position using the mouse and dragging the unit's icon to the desired position. Once at a given position, the C3Fire units automatically start mobilizing and fighting fires or begin the water refill process. More precisely, firefighters are dispatched to water tankers to coordinate refills, firefighters are dispatched to selected high priority areas, water tankers are sent to lakes to refill themselves, water tankers are dispatched to firefighters in order to refill their water supply and reconnaissance units are dispatched to the selected areas to explore.

Monitoring plan outcomes refers to evaluating the results of the previous actions. It is closely related to situation assessment but implies selectively checking the results of past actions. Monitoring plan outcomes is divided into three subtasks: check for firefighting outcome, check for completed refills and check for detected fires. Check for firefighting outcome means looking for closed-out, burned out or burning cells that were targeted, and modify the plan if needed (i.e., the cell burns out) or when the plan is completed (i.e., the fire is extinguished). Check for completed refills means monitoring water levels in order to optimize its efficiency and avoid units remaining idle. Finally, checking for detected fires in the reconnaissance units' visual field (and checking that the unit is still moving) is necessarily an ongoing activity, linked to the fire detection subtask in situation assessment.

The cyclic (but not strictly sequential) nature of situation assessment and resource management (represented in the HTA diagram shown in Figure 18) is in line with the classic representation of the military decision cycle called the OODA loop [5]. OODA stands for a set of four basic processes: Observe → Orient → Decide → Act. Interestingly, Observe and Orient are clearly aligned with the notion of situation assessment, while Decide and Act naturally correspond to resource management. Interestingly, the hierarchical task analysis successfully represented the specifics of the C3Fire task while retaining the general characteristics common to all command and control tasks.

4.3.3 HTA+ analysis

For the present research project, we sought to complement the task analysis with a specification of *information* requirements, interaction with *tools*, specific *actions* to perform, and *events* that trigger each subtask at level 3 of the HTA. This additional analysis provided a more comprehensive characterization of the simulated C2 task. The choice of these four attributes to complement the HTA analysis was inspired by the GTA [76]. This extension of the hierarchical task analysis of C3Fire, detailed below, is referred to as the HTA+ analysis. This analysis was developed by one the SME-analysts and revised by a postdoctoral researcher with extensive knowledge of C3Fire.

[1.1.1] Identify cell state

Information: Cell color
Tools: Map
Actions: Scan map (move eyes on the map), perceive and discriminate brown, black and red cells, make a link between the color of the cell and its actual state
Event: Beginning of a scenario, end of a plan, periodical

[1.1.2] Monitor wind

Information: Wind speed, wind direction
Tools: Wind panel
Actions: Check wind panel, identify the direction towards which the arrow points, identify the numeric representation of the wind speed, deduce the actual speed of the wind
Event: Beginning of a scenario, end of a plan, periodical

[1.1.3] Evaluate workforce status

Information: Unit position, unit activity, unit's destination, unit level of water
Tools: MAP, unit info panel
Actions: scan map to perceive and recognize units' icons, determine relative position of the units, assess the current activity of each unit, assess the level of water of each unit, identify units that need water, scan map to perceive unit destination (white number), evaluate distance between the units and its target.
Event: Beginning of a scenario, end of a plan, current monitoring

[1.1.4] Locate residential areas

Information: Houses position
Tools: Map
Actions: Move eyes on the map, perceive and recognize house’s icons
Event: Beginning of a scenario, end of a plan, periodical

[1.1.5] Locate lakes

Information: Position of each lake
Tools: Map
Actions: Move eyes on the map, perceive and recognize lakes’ icons
Event: Beginning of a scenario, when refilling WT

[1.1.6] Locate forests

Information: Birches forest position, pine forest position
Tools: Map
Actions: Move eyes on the map, perceive and recognize birches’ icons, perceive and recognize pines’ icons
Event: Beginning of a scenario, end of a plan, periodical

[1.2.1] Evaluate fire progression

Information: Cell states (clear, burning, burned-out, closed-out)
Tools: Map
Actions: Assess overall size of fire(s), areas of containment and vulnerable areas
Event: Beginning of a scenario, current monitoring

[1.2.2] Estimate future resources availability

Information: Units’ state previously assessed
Tools: Unit info panel
Actions: Use the information previously found about units’ state to predict which one will soon need to be refilled and which one will be ready for action
Event: Beginning of a scenario, current monitoring

[1.3.1] Determine distance from fire

Information: Fire position, Houses position
Tools: Map
Actions: Scan map, get a global idea of the distance between fire and houses
Event: When making plan

[1.3.2] Estimate spreading speed and direction

Information: Fire position, forests position, wind speed and direction
Tools: Map, wind panel
Actions: Predict the evolution of the fire by taking into account the force and direction of the wind and the forest type present around the current fire. Take into account the presence of closed out cells blocking fire progression
Event: Current monitoring

[1.3.3] Assess risk level

Information: cell contents (forest, house), fire progression
Tools: Map, wind panel
Action: Integrate information to estimate strategic importance of a cell and risk immediacy. See if there is a house or forest in the selected area, and consider cell states and contents in the adjacent area
Event: When making plan

[2.1.1] Select area priority

Information: Risk level of each cell
Tools: Map
Actions: Compare different areas based on the threat previously assessed, choose area that needs to be protect first
Event: When making plan

[2.1.2] Determine water refill priority

Information: Units' water level, FF proximity to WT, WT proximity to lakes
Tools: Map, Unit info panel
Actions: Choose units that need to be refilled first based on water level. To refill a FF, compare distance of WTs. Choose nearest WT with enough water to refill FF. To refill a WT, compare distance of lakes to WT, choose nearest lake
Event: Need of refill, end of a refilling process

[2.1.3] Direct terrain reconnaissance

Information: Unexplored area, time passed since the last recognition in a determine area, position of the rec units
Tools: Map, unit info panel
Actions: Look at the position of the rec units, find the closest unexplored area, or the closest area that has not been explored recently, choose an area
Event: End of recognition in an area

[2.2.1] Dispatch FF to WT (To coordinate refill)

Information: WT position, FF position
Tools: Map, mouse
Actions: Click on the chosen FF icon, drag it beside the chosen WT
Event: One or two empty FF near a WT that can refill up to two FF at a time

[2.2.2] Dispatch FF to high priority coordinates

Information: High priority coordinates, FF position
Tools: Map, mouse
Actions: Click on the FF icon, drag the destination icon to the priority area
Event: Inactive units, new critical event, priority has been established

[2.2.3] Dispatch WT to lake

Information: Lake position, WT position
Tools: Map, mouse
Actions: Click on WT with the cursor, drag the destination icon beside the nearest lake previously identified
Event: Empty WT, inactive WT with little amount of water, priorities have been established

[2.2.4] Dispatch WT to FF

Information: FF coordinates, WT coordinates
Tools: Map, mouse
Actions: Click on the WT with the cursor, drag it beside the FF
Event: Empty FF

[2.2.5] Dispatch rec units

Information: Unexplored area, areas that have not been explored for a while
Tools: Map, mouse
Actions: Click on rec unit with cursor, drag it in the chosen area
Event: End of reconnaissance in a selected area

[2.3.1] Check for firefighting outcome

Information: Cells state, FF position
Tools: Map
Actions: Check unit info panel, identify inactive FF, check map to identify color of the cell under the unit's icon, determine the success or failure of the FF action
Event: Plan has been executed

[2.3.2] Check for completed refills

Information: Water level of each unit, unit's activity
Tools: Unit info panel
Actions: Check unit info panel, identify units that just finished refilling process, check their water level to assess the success or failure of the refilling process
Event: Plan has been executed

[2.3.3] Check for detected fire in rec units visual field

Information: Cell state, rec units position and movement destination
Tools: Map
Actions: Monitor if new red cells appear in the rec unit's visual field, check if rec unit has reached its movement destination
Event: Plan has been executed

4.4 Discussion

We performed a hierarchical task analysis of C3Fire in order to provide a detailed characterization of the taskload involved in this simulated C2 task. We also extended this analysis by identifying the information requirements, the tools, the events and the actions associated with each subtask in order to provide a more exhaustive assessment of workload requirements. This work is a key step in developing a method for estimating the costs and benefits of different team structures.

One aspect that is missing in the current analysis due to an inherent limitation in HTA is the explicit allocation of subtasks to individual agents. The allocation of subtasks to different team members necessarily creates dependencies between team members that require teamwork (e.g., communication, coordination). These dependencies cannot be represented in an HTA or any other current form of task analysis. This constitutes one of the key challenges that will be undertaken in the next step of this research: to develop an approach for representing agents, tasks, tools and teamwork in an integrative framework. The envisioned approach represents teams as sociotechnical systems where interactive behaviour depends on 1) the set of subtasks associated to each team member, 2) on the set of tools required by each agent to accomplish its role, and 3) of the nature and extent of team interactions. This analysis will integrate the task decomposition, the HTA+ analysis and data from the C3Fire experiment in order to develop a model relating team structure, workload and team effectiveness:

One reason for the endurance of HTA is that it can provide a comprehensive model of a sub-goal hierarchy in a system. […] The sub-goal hierarchy lends itself to all manner of analyses, which is the real point of HTA. HTA was never meant to be the end point in the analyses, just the start [64, p.77).

4.4.1 Directions for future research

Team tasks such as C2 can be characterized as cognitively complex and embedded in a sociotechnical environment [78]. We believe that psychological and social processes are best studied in the context of the Task/Tool/Human triad [79; 80] shown in Figure 19.

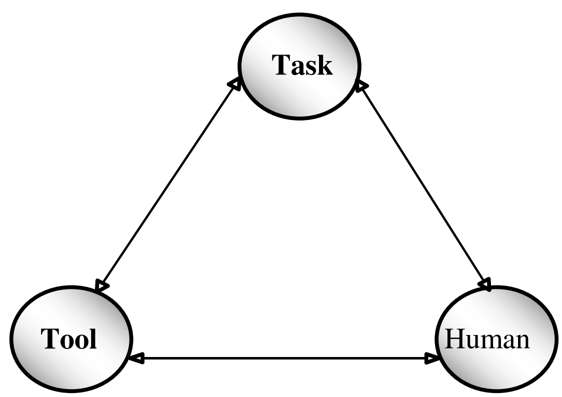


Figure 19: The TRIAD framework [79; 80].

The Rousseau and Price model is a simple network in which three nodes are linked on a one-to-one basis. These nodes are: the Task, the Tool and the Human. The TRIAD approach constitutes an important step in acknowledging the role of these three interacting elements in the study of distributed cognition, human-computer interaction and team modeling. Likewise, Gray and Altmann [81] suggested that the behaviour of a joint cognitive system arises from the limits, mutual constraints and interactions between and among each element of the cognition-artefact-task triad.

This approach suggests that further advances in task analysis should come from combining task decomposition with a graphical representation of the allocation of subtasks across team members and an analysis of the interdependence that it creates between human nodes. Accordingly, a sociotechnical task analysis should provide a way to represent 1) each human agent's *taskwork*, *2)* the extent to which each agent must *interface with tools*, and 3) the *teamwork requirements* that arise when interdependent tasks or unique tools are distributed across agents.

Hollnagel [82] developed the Functional Resonance Accident Model (FRAM) to analyze accidents or to perform risk analysis relative to complex dynamic systems:

> "Complex systems, such as socio-technical systems, are by definition composed of a number of subsystems, which in turn may comprise multiple functions. Although the technological and human (individual, organisational) system components are designed to function in a reliable and predictable manner, performance is always variable to a smaller or larger extent. If a subsystem or a component is considered by itself, this performance variability can be seen as a weak modulated signal, which normally is undetectable, i.e., it is within the limits of tolerance of the system. In relation to any subsystem or component, the rest of the system is the environment. This environment consists of a number of subsystems, for each of which the performance also is variable. Relative to the subsystem under consideration, the aggregated performance variability of this "environment" can be understood as random noise, and it is this random noise that can give rise to resonance, i.e., to a performance variability that is too high" [83].

Figure 20 illustrates the loss of system control when performance variability is too high.

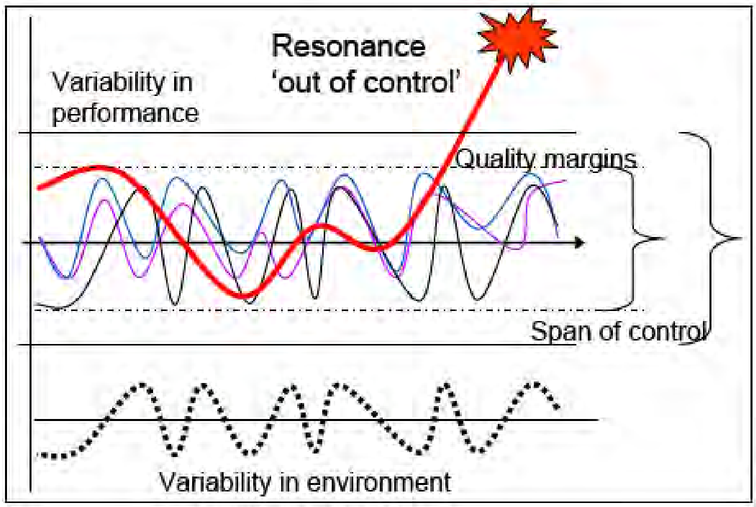


Figure 20: The functional resonance accident model [82].

The FRAM analysis requires four steps:

18. Identify and characterize essential system functions
19. Characterize the (context dependent) potential for variability using a checklist
20. Define functional resonance based on identified dependencies among functions
21. Identify barriers for variability (damping factors)

Though most aspects of the FRAM analysis are not directly relevant to the present research, the first step – characterizing essential system functions – may point to a possible formalism to model the workload of each agent based on his role(s) and relation to other agents. In FRAM, the characterization of each system function is based on a hexagonal representation with six connectors. Multiple functions can be related by these connectors to form a complex network of functions. Figure 21 illustrates the structure of a FRAM module.

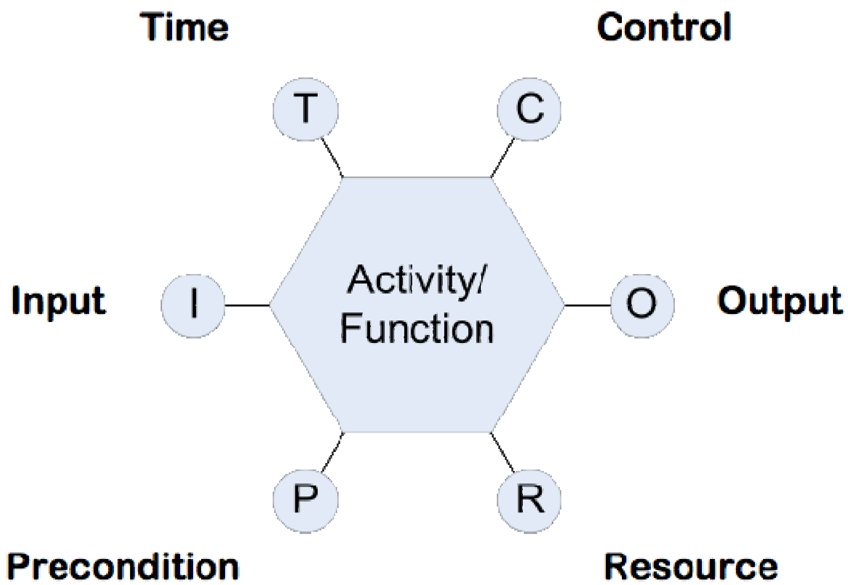


Figure 21: Generic FRAM module.

The *input* (I) of a function corresponds to the characteristics of the situation. The *output* (O) corresponds to the result of the activity or function. *Preconditions* (P) represent conditions that must be satisfied to accomplish the function. *Resources* (R) necessary for the activity must be identified, as well as the temporal constraints (T) to accomplish the function. The sixth element corresponds to *Controls* (C) that serve to supervise or restrict the function. A complex system may invole many interrelated functions with feedback or feed-forward connections. The output of some functions may act as preconditions, inputs, resources or even as a source of control/influence to other functions.

Woltjier, Smith and Hollnagel [84] performed a FRAM analysis on a subset of tasks required in C3Fire. Figure 22 illustrates the resulting functions and their interrelation.

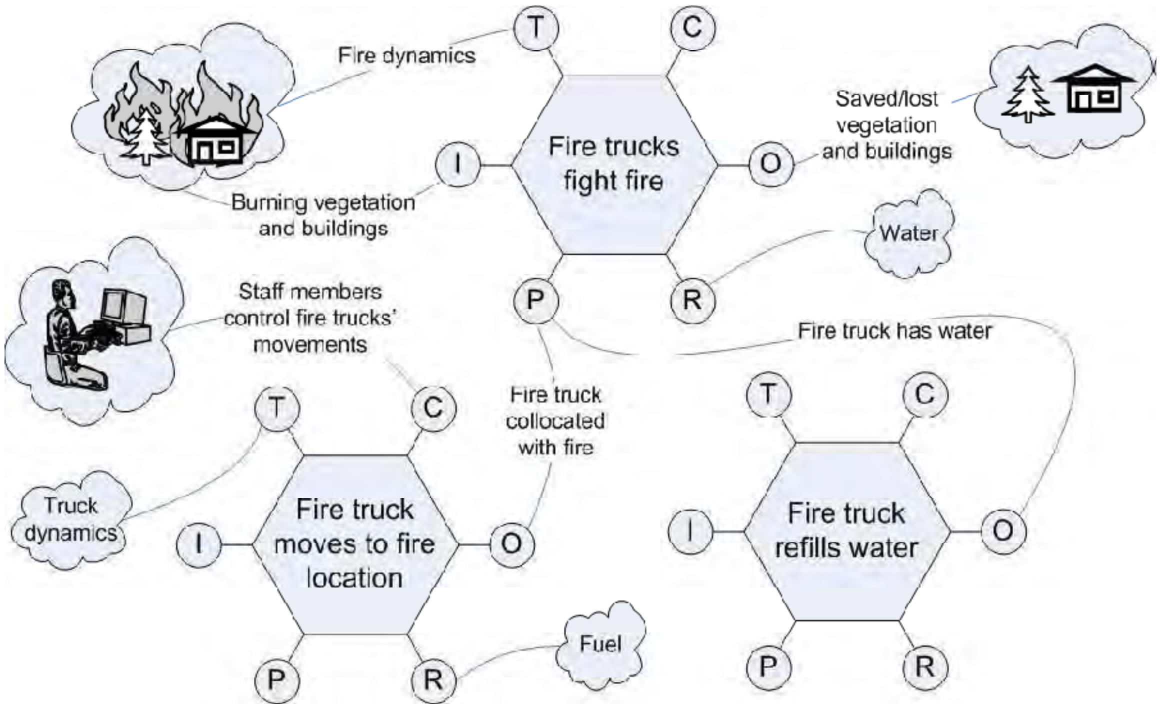


Figure 22: FRAM analysis of C3Fire.

The FRAM analysis provides a useful way to represent functions and constraints related to task execution. The interdependence between subtasks in particularly well described. However, the FRAM analysis of C3Fire is not ideal to characterize teamwork since it is centered on functions rather than on individuals. A variant of this approach with agents as the focal point would be more appropriate to characterize the workload of each individual as a function of his role(s). The role(s) of an agent would determine the tasks/functions that he must accomplish, the prerequisites for performing these functions, the tools required, and the teamwork necessary to achieve the collective goal. This would provide an excellent basis for estimating the workload of individuals and for representing dependence relations between team members as a function of team structure. Such an approach will be developed in Section 5.

5 Integration

This final section combines elements from the statistical modeling approach developed in Section 3 and the results of the task analysis from Section 4 in order to develop a new mathematical model on how team structure impacts team performance. First, the HTA results are used to characterize the taskwork of participants as a function of their role within the team structure (firefighting, water-provisioning, or both). Second, the *Information-Tools-Events-Action* analysis performed to extend the HTA helped identify the tools that participants must interact with depending on their role. The HTA+ analysis thus refers to the combination of these two analyses. These elements are integrated to form a task-to-agent mapping inspired from the FRAM [84] and GTA [76] frameworks and can be considered an extended form of the sociotechnical TRIAD [79] described earlier in this report. The task-to-agent mapping also identifies task dependencies between participants and teamwork requirements that result from these dependencies (i.e., resource-oriented coordination), together with other teamwork processes relevant for the simulated C2 task.

The mathematical modeling approach adopted here consists in estimating the workload of each participant based on the task-to-agent mapping and modeling the relation between workload and individual performance. Next, the model relates individual performance to team effectiveness by taking into account interpersonal dependencies imposed by the team structure. After calibrating the model using results from the C3Fire experiment, we demonstrate how it can be used to estimate the effectiveness of other possible team structures. We conclude with a discussion of the potential and limitations of the present approach and propose directions for future work.

5.1 Basic assumptions of the model

The experimental findings reported in Section 3, together with other results from the team literature [50; 70; 71; 85], show that there is an apparent trade-off between the costs of interpersonal coordination and the benefits of task specialization in functional teams. This trade-off can be either beneficial or detrimental to functional teams depending on whether the task is repetitive and predictable or not [71]. Functional teams are more effective than multifunctional teams in predictable situations because interpersonal coordination can be achieved simply by relying on routine procedures (i.e., planned coordination that requires little communication). However, interpersonal coordination is considerably more demanding in situations that involve constant change and are less predictable. Functional teams are therefore penalized under these conditions because they require more interpersonal coordination than multifunctional teams.

In the present study, our effort is focused on C2 team effectiveness in complex and dynamic situations (see also [86]). The cost of interpersonal coordination is thus expected to be high due to the rapidly changing nature of the situation. Still, there are two additional factors that may further explain the rather low performance of functional teams observed in our experiment: *workload imbalance* and *task dependency*. First, while there is no significant difference in the overall workload of functional and multifunctional teams, there is a *workload imbalance* among members of functional teams. Participant X_F, in charge of controlling all six water-tankers, generally reports having a higher workload than Participants Y_F and Z_F, who are each in charge of 3 firefighters. This result can be easily explained by the fact that a distribution of 4/4/4 units in the

multifunctional structure would produce a more balanced workload than a distribution of 6/3/3 units. It is therefore possible that functional teams were disadvantaged compared to the multifunctional teams in part because Participant X_F was overloaded. Second, functional teams are characterized by *interpersonal task dependency*. A functional task allocation tends to make some team members depend on others due to task dependency. In the case of C3Fire, Participants Y_F and Z_F need water from Participant X_F to perform their task correctly, so overloading Participant X_F can be very detriment to overall team performance. Individual workload and interpersonal dependency will lie at the heart of the mathematical model described later in this section.

The mathematical model has a different purpose than the regression models. The two regression models, one for functional teams and one for multifunctional teams, highlight key similarities and differences in the dynamics of these two team structures. The analysis related team processes or states (coordination, communication, and perceived workload) to team performance and suggested that communication requirements change as a function of team structure. That was a novel result with important implications. For example, future research should no longer attempt to identify a general model of team performance that uses team processes as predictor variables because the role of these processes is not the same from one team structure to another.

Since the regression models seem to be structure-specific, they cannot constitute appropriate tools for predicting the effectiveness of other team structures. Another limit of the multiple regression approach is that the predictors of team performance require measurements of team activity. Such an approach would be of little use for predicting the effectiveness of different team structures since they would have to be tested in order to obtain the value of the regression predictors (coordination, communication, etc.). What is needed here is a set of structural factors that can be used to determine *in advance* the expected effectiveness of a team [55; 87; 88].

The mathematical model does not attempt to account for the different performance of each team in the experiment as a function of team processes like the regression models did. Instead, the model seeks to predict the average performance of teams as a function of team structure. The model does not attempt to explain differences between teams having a same team structure (other *non-structural* factors are responsible for this, e.g., motivation, skill, cohesion, leadership, etc.). Nonetheless, an important similarity between the earlier regression models and the mathematical model proposed here is that both use a similar method to estimate unknown parameters. Both use a least-squares minimization method to reduce as much as possible the difference between model predictions and empirical data [89].

The purpose of the mathematical model is to provide a tool for predicting the effectiveness of different team structures. This method for estimating the costs/benefits of different team structures combines the two distinct approaches described in the previous sections: 1) the analysis of team performance in a simulated task (i.e., C3Fire) using statistical modeling and 2) the analysis of the C2 task simulated in C3Fire using hierarchical task decomposition. First, we will characterize the key differences between functional and multifunctional structures in order to explain how these structural factors lead to differences in team performance. We will perform a task-to-agent mapping that builds on the results of the HTA. This mapping will enable us to identify interpersonal task dependencies and the types of activities associated with each agent (taskwork, teamwork and interaction with tools) will provide the basis for assessing the relative

workload of individuals in each team structure. Second, theses structural factors will constitute inputs to the mathematical model described afterwards.

The model will attempt to account for team effectiveness by:

22. Estimating individual workload;

23. Mapping workload to individual effectiveness;

24. Constraining individual performance as a function of dependency on others;

25. Aggregating the constrained effectiveness of each individual.

Part of the model attempts to describe the relation between the task-to-agent mapping and perceived workload. A second part aims to map workload (associated with taskwork, teamwork and interaction with tools) to individual performance using a nonlinear transfer function described later. A third part of the model relates individual effectiveness to team effectiveness while considering the influence of task dependency between team members (e.g., a participant controlling only firefighters needs water from another participant with water-tankers).

The model developed in this section provides a theoretical account of the effects of team structure on team effectiveness. Taskwork is distributed in different ways among team members depending on team structure. This leads to different dependency relations and teamwork requirements as a function of team structure. The mathematical model aims to relate team structure to team effectiveness using a construct relevant to all team structures: the workload of each individual. The concept of workload includes (1) the various subtasks assigned to the participant, but also (2) the *interaction with tools* and (3) the *teamwork* necessary to accomplish individual and team goals. A basic assumption of the model is that for any team structure, if all participants (correctly) perform their respective teamwork and taskwork, using the tools required for these actions, and then team performance shall be optimal. We assume that what reduces team performance is the difficulty to accomplish this work when team members suffer from high levels of workload.

In summary, the present theoretical perspective proposes a task-to-agent mapping based on the HTA+ analysis in order to provide a qualitative assessment of the workload of each participant as a function of team structure. The mathematical model quantifies the impact of each element of that mapping on individual workload and specifies the functional relationship between individual workload and team performance.

5.2 Task-to-agent mapping

In order to model the effects of team structure, it is necessary to identify how various structures differ. The essential difference between team structures is how sub-tasks are allocated. However, different *task allocations* also have an impact on the *teamwork* required to accomplish the task. An integrative representation of the workload of each individual must therefore include both the *taskwork* and *teamwork* required to accomplish the mission [29; 31; 90]. Task allocation also influences the *tools* that each participant must interact with and the *dependency relations* between participants. The task-to-agent mapping aims to characterize the demands made on each individual along each of these four dimensions.

A first step toward this goal was to perform a hierarchical task analysis to decompose the C3Fire task into a set of subtasks. We also complemented the task analysis with a specification of *information* requirements, interaction with *tools*, specific *actions* to perform, and *events* that trigger each subtask (at level 3 of the HTA). This additional analysis provided a more comprehensive characterization of the simulated C2 task. The choice of these four attributes to complement the HTA analysis was inspired by the FRAM framework [84] and the Groupware Task Analysis [76]. The combination of these two methods constitutes the HTA+ analysis.

There are two possible roles in the current C3Fire experiment: firefighting and water-provisioning. Each team member can either specialize in one role or perform both roles, depending on the team structure. Before performing the task-to-agent mapping, we first associated each subtask in the HTA to each role based on the types of units that the participant controls. We also matched the tools previously identified in the HTA+ analysis as necessary to perform each subtask to each role. For the present analysis, we focused on subtasks at level 3 in the HTA rather than level four. This level was the focus of the HTA+ analysis because some subtasks were not decomposed beyond level 3 in the HTA. This is the finest level of detail that could be selected for the present analysis. Figure 23 presents the results of this task-tool-role mapping.

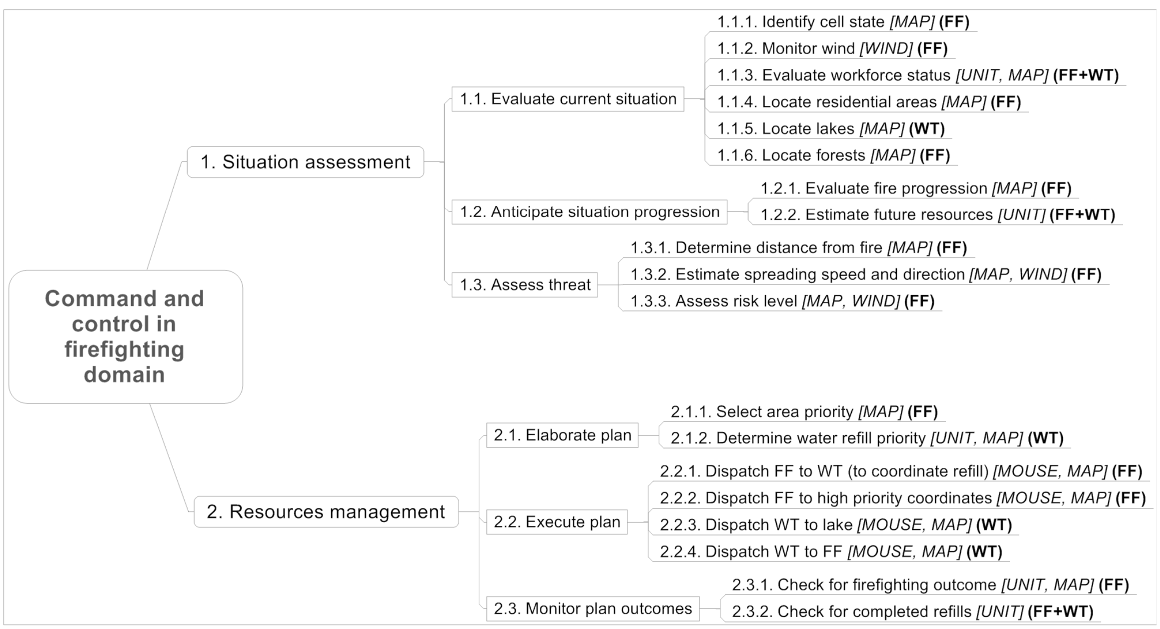


Figure 23: Edited HTA representation, with tasks associated to specific roles and tools. FF = firefighting role, WT = water-provisioning role, MAP = Geospatial information display, UNIT = Unit information panel, WIND = Wind information panel, MOUSE = Computer mouse.

While the HTA provided an informative decomposition of taskwork, it did not identify activities related to teamwork. Four teamwork processes commonly found in the literature were identified by studying communication recordings from the C3Fire experiment: Information sharing, backing up behaviours, goal-oriented coordination and resource-oriented coordination. These activities can be defined as follow:

- Information sharing [91; 92] occurs for example when a participant detects and communicates a critical change such as a new fire or a change in wind strength and direction.
- Backup behaviors [93] include directing a teammates' attention to an unattended unit, making suggestions on how to perform better, finish extinguishing another teammates' fire when he/she runs out of water.
- Goal-oriented coordination is when participants make decisions about priorities or develop strategies on how to fight the fire.
- Resource-oriented coordination refers in C3Fire to the need to communicate the need/offer for water, provide unit position and confirm one's intentions when the firefighting and water-provisioning roles are distributed in an exclusive manner between team members.

Our distinction between these two forms of coordination is inspired by Coordination Theory [68]:

> "According to coordination theory, [team activities] can be separated into those that are necessary to achieve the goal of the process (e.g., that directly contribute to the output of the process) and those that serve primarily to manage various dependencies between activities and resources" (p.159).

Three important tools in C^{3}Fire were not identified in Figure 23 because they are related to teamwork rather than taskwork. The *coordinate system* (letters and numbers on the left and top of the geospatial map) and the *pointer position panel* are essential when two individuals must coordinate the movements of their FF/WT units to perform a water refill (team members do not see their respective units on the map unless they are very close). While the participant controlling a FF unit can simply provide the FF unit's coordinates to his teammate using the information displayed in the unit info panel, the one sending the WT unit to that position must use the coordinate system and the pointer position panel to dispatch his unit to the correct location. The third tool is the *communication button* (together with the headphones), which is essential for goal-oriented and resource-oriented coordination, information sharing and backing up behaviours.

Figures 24 and 25 show the task-to-agent mapping of the multifunctional and the functional team structures along the four dimensions hypothesized as key structural factors of team workload and effectiveness: taskwork, teamwork, tool interaction, and prerequisites (i.e., interpersonal task dependency). Taskwork is subdivided in two distinct functions: situation assessment and resource management. Information is acquired through *situation assessment*. Participants who perform many roles (i.e., who control both FF and WT) have more information requirements than those who perform a single role (i.e., with only one type of unit to control). For example, participants who only control WT do not require information about the localization and state of households. Participants who only control FF do not need information on the position of lakes. More precisely, participants having a pure water-provisioning role will need to perform only 3 out of the 11 third-level subtasks. Participants with only the firefighting role will need to perform 10 out 11 tasks. Participants with both roles will need to perform 11/11 subtasks. Information requirements (i.e., SA requirements) are therefore greatly reduced when a participant specializes in water-provisioning but only marginally reduced when a participant specializes in firefighting, compared to a participant performing both roles.

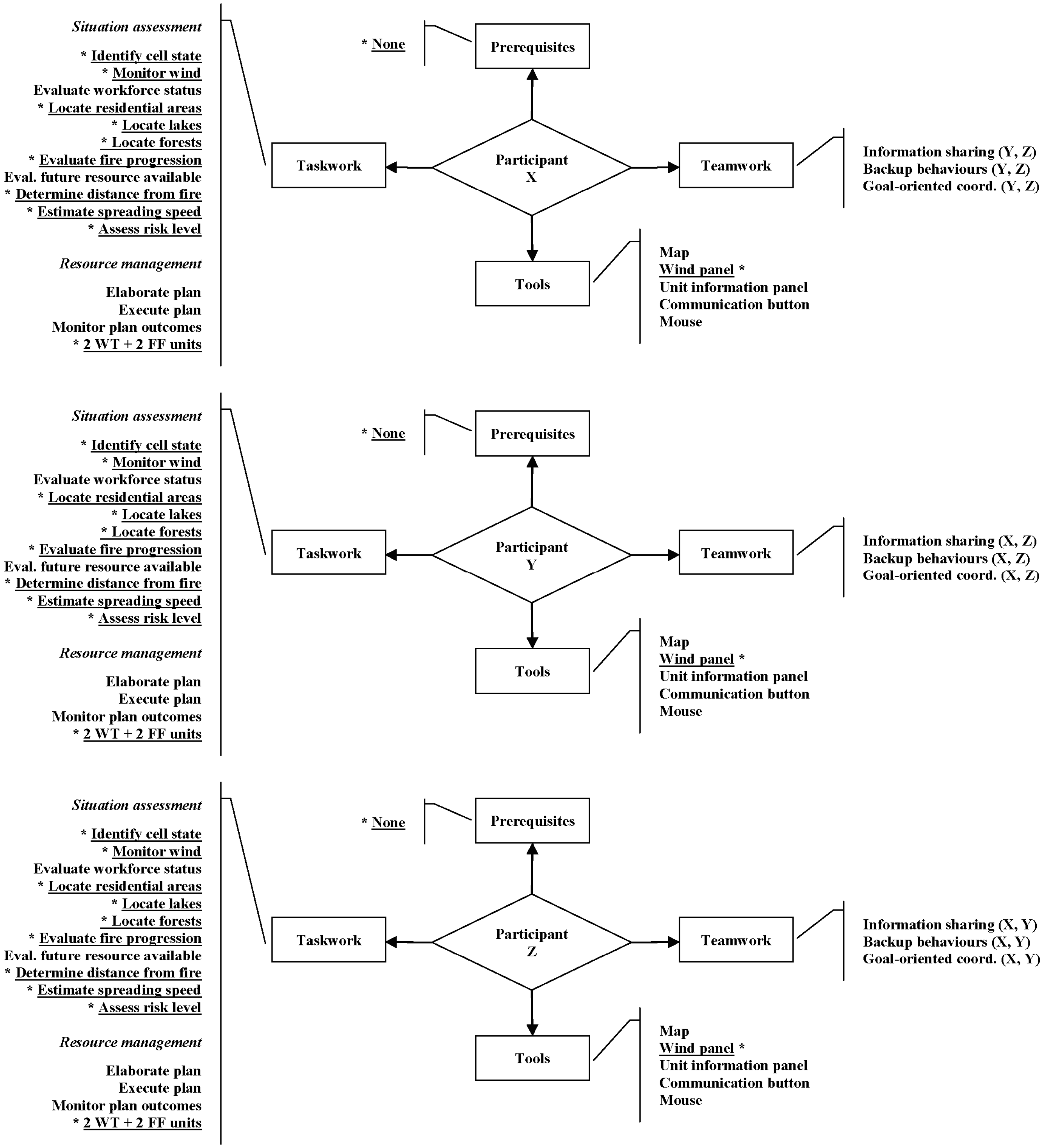


Figure 24: Task-to-agent mapping of the multifunctional team structure.

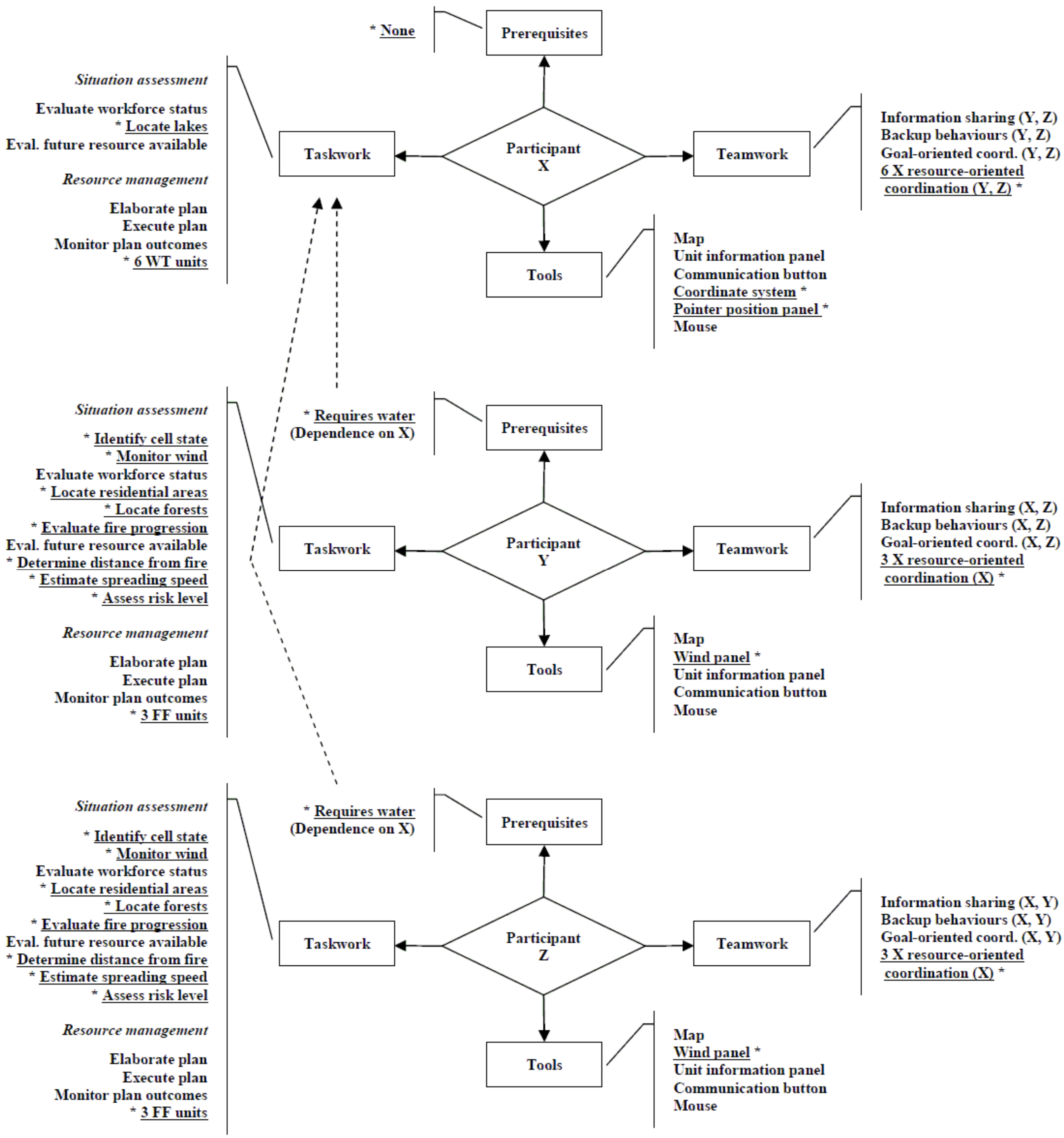


Figure 25: Task-to-agent mapping of the functional team structure.

The workload associated with *situation assessment* and *tool interaction* in the task-to-agent mapping is determined by allocating HTA subtasks to participants according to the roles they perform and the task-tool-role diagram shown in Figure 23.

For resource management, taskwork depends on the number of units to control *and* on the subtasks that must be performed for each unit. While there are various resource management subtasks at level 3 in the HTA, only *one* of these subtasks can be relevant at given time. For example, within the plan execution category, “dispatch WT unit to FF” and “dispatch WT unit to lake” are mutually exclusive. Only one of these two actions is relevant for a given WT unit depending on the plan elaborated for that unit. Here is a second example: When monitoring plan outcomes for a given FF unit, the participant will either check the firefighting outcome or check if the refill is complete (not both), depending on the plan executed for that FF (firefighting or refilling). We therefore assume that for each unit, a participant must manage three activities in a cyclic manner: one of these activities is related to plan elaboration, another to plan execution and a third to monitoring plan outcomes.

A numerical estimate of management workload can thus be obtained by multiplying the number of units controlled by this fixed number of three subtasks. For instance, if a participant controls four units, management workload is determined by multiplying 4 (units) by 3 (subtasks), giving a workload estimate of 12.

To recapitulate, the contents of the *taskwork* and *tool* nodes in the task-to-agent mapping are determined by the task-tool-role diagram shown in Figure 23. The role(s) of each participant (firefighting, water-provisioning, or both) depends on the units that he controls. Next, the teamwork node lists the collaboration processes that each participant must perform and how many resource-oriented coordination processes are required as a function of the number of units controlled. Teamwork requirements were identified by considering task dependency between agents and finding the basic team processes relevant to the simulated C2 task.

This leaves us with the *prerequisite* node which identifies interpersonal task dependency. Clearly, a key precondition of firefighting is having water. In functional teams, the performance of Participants Y_F and Z_F necessarily depends on the effectiveness of Participant X_F in providing water to the FF units. Unlike the other elements of the task-to-agent mapping, a prerequisite is not seen as a factor that contributes to an individual’s workload, but rather as a constraint on the performance of a team member who depends on the actions of a teammate.

We underlined some key elements in the task-to-agent mapping and placed a star besides them to identify those components that are not constant for all participants. It is what varies here that helps the most in explaining workload differences either within a team or between two structures. There are three distinct task-to-agent mappings amongst the six ones described in Figures 25 and 26. The three participants in the multifunctional team structure have the same mapping. In the functional team structure, Participant X is different from Participants Y and Z.

Table 7 summarizes the various sources of workload identified in the task-to-agent mapping for the multifunctional and the functional team structure. The numbers correspond to the (unweighted) workload associated with the tasks or processes relevant to each dimension. The values shown in Table 7 constitute the input for the mathematical model.

Table 7: Structural factors influencing workload in functional and multifunctional teams.

Participant & structure	Situation assessment	Resource management	Tool interaction	Teamwork	Prerequisites
Multifunctional					
Participant X_M	11	12	5	3	-
Participant Y_M	11	12	5	3	-
Participant Z_M	11	12	5	3	-
Functional					
Participant X_F	3	18	6	9	-
Participant Y_F	10	9	5	6	Water from X
Participant Z_F	10	9	5	6	Water from X

The task-to-agent mapping shows that the main benefit of functional specialization comes from having reduced SA requirements, especially for the water-provisioning role. The main cost of functional specialization is the increased amount of teamwork necessary to coordinate with others.

5.3 Quantitative modeling

Here, we propose a theoretical account of the factors that determine individual workload, we use a mathematical function to characterize how humans deal with increasing levels of workload and how team structure modulates the relationship between individual performance and team effectiveness. Once calibrated on the data from the C3Fire experiment, the model can serve as a tool for predicting the effectiveness of other team structures.

The mathematical model uses the empirical data from the C3Fire experiment as a set of constraints for estimating its key parameters. The model does not attempt to explain differences between team having a same structure; it only seeks to explain the general difference between structures.

Table 8 shows the average performance of each team on the four test scenarios. Team performance was defined by the number of fires put out (i.e., offensive aspect) multiplied by proportion of houses saved (i.e., defensive aspect). Performance was converted in percent rank scores to make comparisons more intuitive. Percent rank is obtained for a given score as follow:

Number of score under a given value / (number of score under the value + number of score above the value)

For instance, 18 scores are under the score (61.84) for team #10 (multifunctional) and 1 is above. Then, 18 / (18+1) = .947.

The average rank of multifunctional teams was 76% compared to 24% for the functional teams. Team structure explains 72% of the variance in the observed performance of the 20 teams analyzed. This means that the model can at best explain 72% of team performance in the present study.

Table 8: Observed performance and percent rank for each team in the C3Fire experiment.

Team structure	Team	Observed performance	Percent rank
Multifunctional	1	57.75	0.84
	2	48.30	0.63
	3	63.21	1.00
	4	45.23	0.58
	5	39.10	0.47
	6	51.44	0.68
	7	56.44	0.79
	8	53.95	0.74
	9	58.33	0.89
	10	61.84	0.95
Functional	11	32.80	0.32
	12	34.18	0.37
	13	38.89	0.42
	14	20.75	0.11
	15	23.23	0.16
	16	7.99	0.00
	17	16.53	0.05
	18	26.75	0.21
	19	29.86	0.26
	20	44.48	0.53

The mathematical model can be described as a chain of *three mappings* to explain team performance (model output) based on team structure (model input):

26. How team structure determines individual workload

27. How workload determines individual effectiveness

28. How individual (and team) effectiveness is constrained by inter-agent dependency

The three components of the model are described in turn below. Then, after calibrating the model using empirical data from the C3Fire experiment, we apply it to new team structures in order to predict their relative effectiveness.

5.3.1 How team structure determines individual workload

The first assumption in the model is that the relative workload of each individual depends on taskwork (situation assessment and resource management), teamwork, and interaction with tools required to accomplish the task. The workload associated with each of these factors was characterized in the task-to-agent mapping and then summarized in numerical form. The mathematical model requires estimating the relative weights of these factors to determine the total workload of each participant on a scale from one to ten (like the measure of perceived workload). Individual workload is computed by summing four subtypes of workload:

$$SA\ workload = Number\ of\ SA\ subtasks \times weight$$

$$Management\ workload = Number\ of\ subtasks \times number\ of\ units \times weight$$

$$Teamwork\ workload = Number\ of\ teamwork\ processes \times weight$$

$$Tool\ workload = Number\ of\ tools \times weight$$

At first, we assumed that the relative importance of each of the four workload factors would not necessarily be equal. The modeling procedure was supposed to involve estimating distinct weights for each subtype of workload. However, preliminary modeling results showed that the model successfully fitted the data with only one weight parameter (plus two other free parameters to define a non-linear function that relates individual workload to effectiveness). Surprisingly, there was no gain in allowing different weights values for each factor. This leads to a remarkably parsimonious quantitative model. Since this weight value is the same for all factors, it basically plays the role of a scaling parameter whose purpose is simply to resize the numerical workload assessment to better fit perceived workload.

The value of the weight parameter was estimated by least-squares minimization using a quasi-newton optimization algorithm. The estimated value was 0.249. The unweighted workload is thus approximately divided by 4 in order to fit subjective workload. There is an extremely strong relation between perceived workload and the simple unweighted workload metric derived from the agent-to-task mapping. In fact, the unweighted workload assessment successfully explains 100% of the variance in perceived workload. This is a remarkable result suggesting that the workload metric based on the task-to-agent mapping represents very accurately the actual workload of individuals. Table 9 shows the observed and estimated workload for each participant in the multifunctional and functional team structures.

Table 9: Average workload ratings reported by participants in the C3Fire study and model fits.

Structure	Participant	Perceived workload	Modeled workload	Unweighted workload
Multifunctional	Participant X_M	7.73	7.74	31
	Participant Y_M	7.73	7.74	31
	Participant Z_M	7.73	7.74	31
Functional	Participant X_F	9.00	8.99	36
	Participant Y_F	7.50	7.49	30
	Participant Z_F	7.50	7.49	30

Note. Perceived workload was rated on a scale from 1 (very low) to 10 (very high). We calculated the average workload ratings of Participants $X_M/Y_M/Z_M$ in the multifunctional structure, of Participant X_F in the functional structure and of Participants Y_F/Z_F in the functional structure.

5.3.2 How workload determines individual effectiveness

The whole point of estimating the workload of individual participants as a function of team structure is that it can then be related to performance. We assume that the relationship between workload and performance is not just linear, but rather that performance remains high as humans compensate (i.e., with increased effort or adaptive strategies) for increasing difficulty and time pressure, then rapidly drops past a point of overload, and stabilizes at some minimum (see [94]). We assume that this relationship follows an inverse sigmoid function. Figure 26 illustrates a generic version of this function.

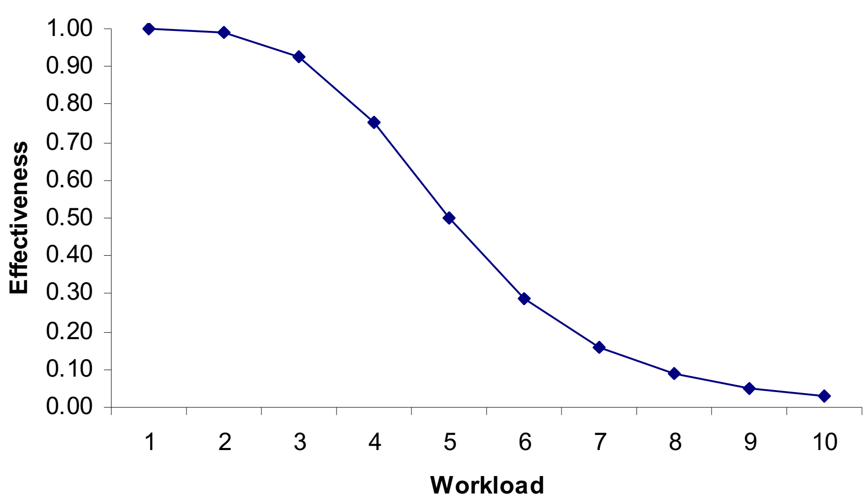


Figure 26: Typical (reverse) sigmoid function (n = 5, k = 5, max = 1).

This function can drop more or less steeply or at different points on the x-axis depending on its parameters. The equation for the reverse sigmoid is:

$$y = max \cdot k^n / (k^n + x^n)$$

where "*y*" corresponds to the output of the function: individual effectiveness. The *max* parameter corresponds to the maximum value of *y*. The *k* parameter is the "half-maximum" of the curve and has the following meaning: when $x = k$, $y = 1/2 \cdot max$. The "*n*" parameter controls how steeply the curve falls. When modeling the data from the C3Fire experiment, the exact shape of the function is estimated by the model using least-squares minimization. The function has one fixed and 2 free parameters:

- *max* is set to *one* (i.e., the optimal effectiveness)
- the estimated *k* value is 8.39
- *n* is estimated to be 14.20

Figure 27 illustrates the functional relationship between individual workload and effectiveness estimated by the model.

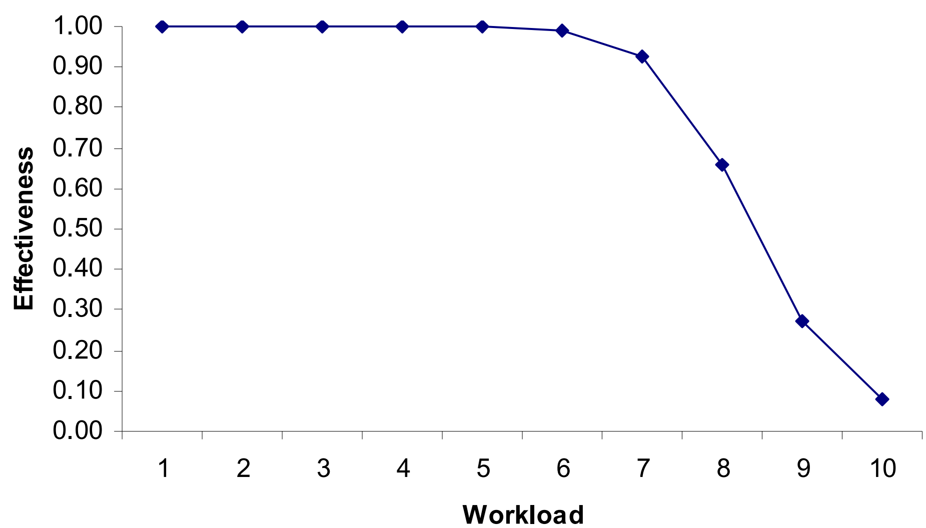


Figure 27: Estimated relation between workload and effectiveness.

Table 10 shows the predicted effectiveness of each team member as a function of its workload. Note that participant X_F is clearly overloaded compared to other participants.

Table 10: Individual workload and predicted effectiveness as a function of team structure.

Structure	Participant	Effectiveness	Workload
Multifunctional	Participant X_M	0.76	7.74
	Participant Y_M	0.76	7.74
	Participant Z_M	0.76	7.74
Functional	Participant X_F	0.27	8.99
	Participant Y_F	0.83	7.49
	Participant Z_F	0.83	7.49

5.3.3 How individual effectiveness is constrained by interpersonal dependency

Despite the very low effectiveness predicted for Participant X_F, the model still cannot adequately account for the large gap between the average performance of functional and multifunctional teams. A key structural difference remains to be added. There is notion of dependency between the participants Y_F and Z_F and participant X_F. The first two participants must accomplish two distinct goals. One is the offensive aspect of the game (closing out the fires) and the other is the defensive one (saving the houses). The goal of participant X_F is only to refill the other two participants' units with water when required. Consequently, the goal fulfillment of the participants Y_F and Z_F is totally dependent of the goal fulfillment of participant X_F. As a result, it becomes a negative constraint on these participants as per the following formalization.

This constraint on the performance of Participants Y_F and Z_F is operationalized by multiplying their effectiveness with that of Participant X_F. The actual performance of Participants Y_F and Z_F is 0.83 (their own effectiveness) * 0.27 (the effectiveness of Participant X_F), for a result of 0.23. Team performance is computed to by averaging the (constrained) performance of all three team members. Table 11 shows the main modeling results: estimated workload, constrained effectiveness and predicted team performance.

Table 11: Workload and predicted effectiveness as a function of team structure.

Structure	Predicted team performance	Constrained effectiveness	Estimated workload	Participant
Multifunctional	0.76	0.76	7.74	Participant X
		0.76	7.74	Participant Y
		0.76	7.74	Participant Z
Functional	0.24	0.27	8.99	Participant X
		0.23*	7.49	Participant Y
		0.23*	7.49	Participant Z

* The unconstrained effectiveness of Participants Y_F and Z_F was 0.83. This value was multiplied by the effectiveness of Participant X_F on which they depend (0.27), giving a constrained effectiveness of 0.23.

The average performance of multifunctional teams in the C3Fire experiment was 0.76. The average performance of functional teams was 0.24. The mathematical model therefore successfully fitted the observed workload ratings and the average performance of each team structure as well as was theoretically possible. Although the model does not account for individual team variability (which depends on other factors than team structure) it successfully explains 72% of the variability in the observed performance of the 20 teams tested. Clearly, team structure is a determinant factor of team effectiveness. The mathematical model provides a good theoretical explanation of how structural factors may have influenced team effectiveness.

5.4 Application to new structures

According to Navarro and Lee [95] a good model should 1) provide accurate descriptions of the available data; 2) confer meaning or offer substantive insight into the phenomena being investigated; and 3) provide predictions and generalize to new or different situations where data are not available. The mathematical model developed here – now that it has been successfully calibrated on empirical data – can serve as a tool to extrapolate how teams should perform on the same task when organized according to other possible structures. Four candidate team structures came to mind:

- An alternate form of the functional organization
- A hybrid team structure (part functional, part multifunctional)
- A four-person functional team structure
- A six person multifunctional team structure

Unit allocation is:

– [X = 6FF // Y = 3WT // Z = 3WT] in the alternate functional structure

– [X = 2FF-2WT // Y = 4WT // Z = 4FF] in the hybrid structure

– [W = 3WT // X = 3WT // Y = 3FF // Z = 3FF] in the 4-functional structure

– [1FF-1WT each] in the 6-multifunctional structure

We performed a new task-to-agent mapping for each of these four test structures. Table 12 summarizes the key structural factors that define the total workload of each participant.

Table 12: Key structural factors influencing individual workload in the four test structures.

Participant & structure	Situation assessment	Resource management	Tool interaction	Teamwork	Prerequisites
Alt. functional					
Participant X	10	18	5	9	Water from Y-Z
Participant Y	3	9	6	6	-
Participant Z	3	9	6	6	-
Hybrid					
Participant X	11	12	5	3	-
Participant Y	3	12	6	7	-
Participant Z	10	12	5	7	Water from Y
4-functional					
Participant W	3	9	6	6	-
Participant X	3	9	6	6	-
Participant Y	10	9	5	6	Water from W
Participant Z	10	9	5	6	Water from X
6-multifunctional					
Participant U	11	6	5	3	-
Participant V	11	6	5	3	-
Participant W	11	6	5	3	-
Participant X	11	6	5	3	-
Participant Y	11	6	5	3	-
Participant Z	11	6	5	3	-

We applied the mathematical model to each of the four test structures in order to infer their relative effectiveness. Predictions were obtained using the parameters that were estimated earlier using results from the functional and multifunctional teams in the C3Fire experiment. Table 13 shows the predicted effectiveness for each of these team structures.

Table 13: Application of the model as a tool for estimating the effectiveness of four team structures.

Structure	Predicted team performance*	Constrained effectiveness	Estimated workload	Participant
Alternate functional	0.69	0.07	10.00**	Participant X
		0.99	5.99	Participant Y
		0.99	5.99	Participant Z
Hybrid	0.70	0.76	7.74	Participant X
		0.93	6.99	Participant Y
		0.42	8.49	Participant Z
4-person functional	0.91	0.99	5.99	Participant W
		0.99	5.99	Participant X
		0.83	7.49	Participant Y
		0.83	7.49	Participant Z
6-person multifunctional	0.99	0.99	6.24	Participant U
		0.99	6.24	Participant V
		0.99	6.24	Participant W
		0.99	6.24	Participant X
		0.99	6.24	Participant Y
		0.99	6.24	Participant Z

* Performance (in percent rank) relative to the performance of the 20 teams in the C3Fire experiment.
** Workload is assumed to be maximal at 10.

- *Alternate functional team.* In an alternate functional division of labour, Participant X has 6 FF, Participant Y has 3 WT, and Participant Z has 3 WT. Participant X depends on both of his teammates for water and he has a maximal workload (the estimated value would be higher but it has been limited to 10). Despite his low effectiveness, Participant X seldom lacks water due to the high effectiveness of Participants Y and Z in replenishing the water reserves of his units.
- *Hybrid team.* It is possible to mix a functional and a multifunctional task allocation within a same team. In this hybrid structure, Participant X is multifunctional. He controls 4 FF and 4 WT units. Participant Y controls 2 WT units and Participant Z control 2 FF units. The model predicts that Participant Z should be overloaded and that this will reduced overall team performance. This hybrid structure, while not optimal in terms of predicted effectiveness, may benefit from a greater adaptability to various situations.

- *4-Person functional team.* An interesting possibility offered by the model is to explore how increasing the number of team members may impact the effectiveness of a given team structure. While a functional division of labor in a three-person team resulted in an overloaded individual, the same may not be true for a four-person team. In this team configuration, Participants W and X control 3 WT each, while Participants Y and Z control 3 FF each. The model predicts that a 4-person functional team should perform markedly better than a three-person multifunctional team (91 vs 76 percent rank).
- *6-Person multifunctional team.* Another potential use for the model is to determine how many people are required to perform the task as well as possible. The model can be used to predict at which point increasing the number of team members no longer provides a benefit. For instance, when six participants each control 1 FF and 1 WT, the model predicts that workload will be sufficiently low so that effectiveness is nearly optimal.

In summary, the mathematical model predicts the following ordering of team effectiveness as a function of team structure:

- 6-Person multifunctional (99%)
- 4-Person functional (91%)
- Multifunctional (76%))
- Hybrid (70%)
- Alternate functional (69%)
- Functional (24%)

6 General discussion

The present work has shown that combining experimental measurement using a microworld, hierarchical task analysis and mathematical modeling can provide a systematic method for estimating the costs/benefits of different team architectures. Current results suggest that the approach has great potential. By providing clear quantitative predictions, the model is highly refutable and can therefore be improved if some predictions do not turn out to be correct. If necessary, the model could also be calibrated on more than just two team structures to increase the reliability of its predictions. Thanks to its great simplicity, this approach has shown that it can obtain stable estimates of its three adjustable parameters (taskwork, teamwork and tool interaction) without requiring excessive empirical data. This method therefore overcomes a fundamental limitation of computational GOMS models and complex cognitive architectures [56] discussed earlier in this report. Such models attempt to characterize processes and subtasks with such detail that estimating the numerous unknown parameters appropriately would require an excessively large number of experimental manipulations and measurements. This problem is similar to the notion of "sample complexity" in machine learning: the more complex the model, the more examples (i.e., constraints) it requires in order to make reliable predictions. This problem applies as well to the TOD and the IPME methodologies described in Freeman et al. [53]. These quantitative modeling approaches involve a model calibration phase based on empirical data in order to generate predictions, just like the method proposed here.

A common element to the mathematical model proposed here, the computational GOMS model, the TOD methodology and the IPME framework is that the concept of workload is very important. In fact, the TOD methodology proposes two alternative ways to model the effects of workload [55]. Figure 28 shows the Gaussian workload function and the inverted quadratic workload function. Note that the latter function is remarkably similar to inverse sigmoid proposed in the present report.

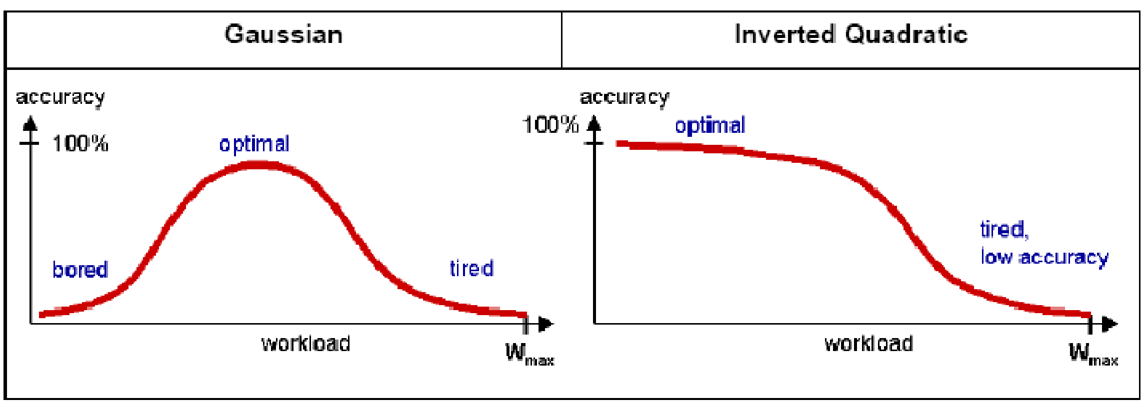


Figure 28: Alternate forms for the effect of workload on operator accuracy

(from [55]).

Despite the similar approach, we argue that the computational GOMS, TOD and IPME models are unnecessarily complex and that this can seriously limit their reliability when calibrated on

limited experimental data. The time, effort, expertise and cost required to develop and apply these models may be greater than necessary. For example, Levchuk et al. [55] model task effectiveness using many variables related to individual characteristics such as initial incompetence, learning and memory (retention of learning). These free parameters are not essential to predict the effectiveness of various team structures and they may provide too much flexibility to these models, thus increasing the risk of noise overfitting [57].

The method taken here to estimate the costs/benefits of teamwork takes an approach that is somewhat similar to the EAST methodology (Event Analysis of Systemic Teamwork). EAST combines a number of human factors research methods to study team activity in a C4I work context (command, control, communications, computers and intelligence), namely:

- Hierarchical task analysis
- Observation (empirical data)
- Coordination demands analysis
- Communications usage diagrams
- Social network analysis
- Operation sequence diagram
- Critical decision method
- Propositional networks

Note that the two first methods in this list (HTA and observation/measurement) correspond to those used in the present study. The task-to-agent mapping accomplishes a purpose similar to coordination demands analysis (defining taskwork and teamwork).

> "EAST provides an assessment of agent roles within the network, a description of the activity including the flow of information, the component tasks, communication between agents and the operational loading of each agent. Coordination between agents is also rated and the knowledge required throughout the task under analysis is defined" [96].

The EAST methodology is an assembly of distinct techniques capable of providing multiple views on team activity. The descriptive capabilities of this approach are extensive. Stanton et al. [96] note however that the method it is very time consuming because it is so exhaustive.

The approach developed here does not apply such a wide range of methods of analysis, yet its greater simplicity and focus have allowed it to produce a mathematical model capable of predicting team effectiveness as a function of team structure. The main novelty of the present method lies in the effort to *integrate* results from each method to produce a well-defined theoretical framework capable of making a priori predictions.

The present project has proposed a new framework for estimating the costs and benefits of teamwork because no prior framework was capable of providing reliable quantitative estimates of team effectiveness based on minimal data collection.

While the FRAM analysis was a major inspiration for the task-to-agent mapping performed here, its objective is not to predict the effects of various team structures on team effectiveness. Hollnagel [83] and Sawaragi, Horiguchil & Hinal [97], used FRAM for safety analysis. Woltjier et al. [84] applied the FRAM method to inform the design of information technology to be used in network-based command-and-control centers. Our framework draws only from "Step 1" in the FRAM analysis, which identifies the functions and constraints on the execution of a task. Like a HTA, the first part of the FRAM analysis is conducted by (or in consultation with) a domain expert. The key difference between the two approaches is that the FRAM modules are centered on functions aimed at process control, while the task-to-agent mapping is centered on each agent (i.e. each agent constitutes a module). Later steps in the FRAM analysis are concerned with identifying the variables that change during task execution and the constraints on these variables. In principle, a different FRAM analysis could be performed for each possible team structure in order to predict the effectiveness of various team structures. However, very few of the key factors or predictors in the analysis (called common performance conditions) are in fact related to team structure:

- Adequacy of organization (related to structure but circular)
- Working conditions
- Adequacy of interface and operational support
- Availability of procedures / plans
- Number of simultaneous goals (related to structure)
- Available time
- Circadian rhythm
- Adequacy of training and experience
- Crew collaboration quality
- Communication (related to structure)
- Availability of resources

The new framework proposed here is therefore more appropriate for predicting team effectiveness as a function of team structure than the FRAM analysis because it relies specifically on factors that vary according to team structure (taskwork, teamwork, tool interaction, interpersonal task dependency).

The structural factors identified in the theoretical model may provide further insights on how to improve performance in functional teams. For example one way to improve the effectiveness of functional teams could be to provide team members with direct access to the key information necessary for resource-oriented coordination (e.g., showing to Participant X_F the position of FF units on the map to facilitate water-provisioning). Automated information sharing (of data relevant to the collaboration process) should help reduce individual workload and avoid the disruptive effects interruptions associated with information requests.

The present work did not take into account team factors such as trust, team cohesion and team members experience working together. Yet, incorporating these factors would allow modelling individual differences across teams. Furthermore, teamwork requirements may evolve throughout the existence of the team. Thus, team mates working for an extended period of time together in a functional structure could have shown better results than in multifunctional one. This question could make the object of future works.

As a final remark, we should add that future research would benefit from a more detailed workload questionnaire since the theoretical model relies heavily on that notion. Despite the great complexity and context dependence of team functioning, this new approach to team design shows that estimating the costs and benefits of teamwork can be performed in a systematic and tractable way. The approach identifies how to balance the workload of C2 teams and can determine how many team members are necessary to optimize team effectiveness in complex and dynamic situations.

7 Conclusion

The next sections summarize major contributions from this research project.

7.1 Identification of team processes

One major impact of this project is to demonstrate that the relationship between key determinants of teamwork and team effectiveness varies as a function of team structure. This demonstration comes from the comparison of the coefficients found in two multiple regression models (for multifunctional and functional teams) relating team performance to a number of predictors of team effectiveness. Key similarities and differences were observed, suggesting that some aspects of team functioning can markedly change as a function of team structure. Since different team structures may rely upon different team processes, it would seem inadequate for future research to employ a general model of team performance that uses a fixed set of standard team processes as predictor variables. The role of these processes is not the same from one team structure to another, and so such processes are an insufficient way to predict the performance of different team structures. The findings presented in this report suggest that teamwork requirements and the importance of various team factors in general may vary as a function of team structure. Obviously, communication and coordination are key components of teamwork, but their relative importance is affected by the manner in which the team is configured. For instance, results showed that communication was positively correlated with team performance in functional teams, but negatively correlated in multi-functional ones.

Depending on the team structure, each team member has to perform particular tasks associated with his or her role within the team. Team members also need to coordinate their interdependent activities, share information and make collaborative decisions on how to deal with the situation. Yet many social and cognitive factors interact to determine team effectiveness under nominal situation and in off-nominal situations in which resilience and adaptation (i.e., team agility) are critical. Are optimally effective teams also the most resilient and adaptive, or is there a trade-off in these properties. It could be argued that resilience needs redundancy, which is typically not the way to maximise effectiveness. There remains a lack of consensus regarding the delimitation and conceptualization of processes and behaviours critical for team effectiveness and agility in the literature on teamwork. Consequently, there is a growing need to understand teamwork and the processes or factors that affect both team performance and agility as well as how these two properties interact. Furthermore, results from this research project highlight the importance of considering that the impact of many of the relevant processes and factors may be structure-dependent.

Our results showed that team performance as a function of team structure can be predicted by mathematical models that use factors such as taskwork, teamwork, tool interaction and interpersonal task dependency. The possibility to use such models in order to identify the optimal type of team structure and the optimal number of team members is promising.

7.2 Workload: a key predictor of team performance

Individual workload and interpersonal dependency lie at the heart of the mathematical model described in this report. Workload is considered as a key predictor of the team performance. The mathematical model can be described as a chain of *three mappings* to explain team performance (model output) based on team structure (model input):

29. How team structure determines individual workload

30. How workload determines individual effectiveness

31. How individual (and team) effectiveness is constrained by inter-agent dependency

Consequently, a critical phase in the development of the mathematical model was to define the concept of workload. The concept of workload was defined by considering various elements shown in the task-to-agent mapping:

32. the various subtasks assigned to the participant;

33. the *interaction with tools*;

34. the *teamwork* necessary to accomplish individual and team goals.

Such decomposition of workload was key to the modeling approach. The correlation between the level of workload perceived by the participants and the results from the model is astonishing. This remarkable result suggests that the workload metric based on the task-to-agent mapping represents accurately the actual workload of individuals.

7.3 Using the model to identify optimal team structure and size

In this project, an experiment demonstrated that using different team structures led to different team performance. We performed a task analysis and developed a structural model (a task-to-agent mapping) that represented team workload and then developed a mathematical model of team effectiveness. The formal model was very successful in accounting for the experimental results. The mathematical model displays two different interesting capabilities:

First, the model can serve as a tool to extrapolate how teams should perform on the same task when organized according to other possible structures. This model capability is very interesting for the identification of optimal team structure in C2 environment.

Another interesting possibility offered by the model is to explore how increasing the number of team members may impact the effectiveness of a given team structure. For instance, the model predicted that a 4-person functional team should perform markedly better than a three-person functional team (91 vs 24 percent rank). This result suggests that adding one person to the team may result in an important increase in the team performance.

7.4 Future works

This report presents results of an empirical test and a mathematical model of team performance with regard to the team structure. The model displays an impressive capacity to replicate the results observed from the 20 three-person teams. Thanks to its great simplicity, this approach has shown that it can obtain stable estimates of its three adjustable parameters without requiring excessive empirical data. From this model, it was possible to predict the performance of four other fictional teams. Three phases should follow the work initiated in this project:

Phase 1: The comparison of the results predicted by the model with the four different team structures (Six-Person multifunctional; four-Person functional; Hybrid; and Alternate functional) with the performance of teams using these different structures. This would provide a test of the specific assumptions proposed in the model and help improve its reliability.

Phase 2: The replication of the results presented in this report with a different microworld in order to generalize the findings and increase the ecological validity of the approach.

Phase 3: The validation of the capacity of the model to assist team design by testing its predictions of performance for real C2 teams in the ecological context of a rapid response planning exercise or integrated C2 experimentation.

References

[1] Curts, R. J., & Campbell, D. E. (2006). Rethinking Command and Control. *Proceedings of the Command and Control Research and Technology Symposium,* San Diego, CA.

[2] Pigeau, R. A., & McCann, C. (2002). Re-conceptualising Command and Control. *Canadian Military Journal, 3,* 53-64.

[3] Ioger, T. R., & He, L. (2003). Modeling Command and Control in multi-agent Systems. *Paper presented at the ICCRTS.*

[4] Klein, G. A. (1993). A Recognition-Primed Decision (RPD) model of rapid decision making. In G. A. Klein, J. Orasanu, R. Calderwood, & C. E. Zsambok (Eds.), *Decision making in action: Models and methods* (pp. 138-147). Norwood, NJ: Ablex Publishing Co.

[5] Boyd (1987). *Organic Design for Command and Control.* http://www.d-n-i.net/boyd/pdf/c&c.pdf

[6] Jagacinski, R.J., & Flach, J.M. (2003). *Control Theory for Humans.* Mayhaw, NJ: Lawrence Erlbaum.

[7] Breton, R., & Rousseau, R. (2005). The C-OODA: A cognitive version of the OODA loop to represent C2 activities. *CCRTS,* McLean, VA.

[8] Salas, E., & Fiores, S. M. (Eds) (2004). *Team Cognition: Understanding the Factors That Drive Process and Performance.* Washington, DC: American Psychological Association.

[9] Mcintyre, R. M., & Salas, E. (1995). Measuring and managing for team performance: emerging principles from complex environments. In R. Guzzo & E. Salas (Eds), *Team Effectiveness and Decision Making in Organizations* (149-203). San Francisco: Jossey-Bass.

[10] Salas, E., Bowers, C. A. & Cannon-Bowers, J. A. (1995). Military team research: 10 years of progress. *Military Psychology, 7*(2), 55-75.

[11] Rousseau, V., Aubé, C. & Savoie, A. (2006). Teamwork behaviors: A review and an integration of frameworks. *Small Group Research*, *37*, 540-570

[12] Salas, E., Sims, D. E., & Burke, C. S. (2005). Is there a "big five" in teamwork? *Small Group Research, 36*(5), 555-599.

[13] Norman, D. A. (1983). Some observations on mental models. In D. Gentner and A. L. Stevens (Eds), *Mental Models* (pp. 7–14). Hillsdale, NJ: Erlbaum.

[14] Perry, M. J., Fruchter, R., & Rosenberg, D. (1999). Co-ordinating distributed knowledge: A study into the use of an organizational memory. *Cognition, Technology & Work, 1*, 142-152.

[15] Fan, X., & Yen, J. (2004). Modeling and simulating human teamwork behaviors using intelligent agents. *Physics of life reviews, 1*(3), 173-201.

[16] Malone, T. W. (1987). Computer support for organizations: Toward an organizational science. In J. M. Carroll (Ed). *Interfacing thought: Cognitive aspects of human-computer interaction.* (pp. 294-324). Cambridge, MA: The MIT Press.

[17] Wasserman, S. & Faust, K. (1994). *Social network analysis: Methods and applications. Structural analysis in the social sciences*. New York, NY, US: Cambridge University Press.

[18] Durfee, E. H., Lesser, V. R., & Corkill D. D. (1987). Coherent cooperation among communicating problem solvers. *IEEE Transactions on computers, 36*(11), 1275-1291.

[19] Gonzalez, C., Vanyukov, P. & Martin, M. K. (2005). The use of microworlds to study dynamic decision making. *Computers in Human Behavior, 21*(2), 273-286.

[20] Brynielsson, J., & Granlund, R. (2001, June). Assistance in Decision Making: Decision help and decision analysis. In Proceeding of the 6th International Command and Control Research and Technology Symposium, Annapolis, Maryland, USA.

[21] Cannon-Bowers, J. A. & Salas, E. (1998). Team performance and training in complex environments: Recent findings from applied research. *Current Directions in Psychological Science*, *7*(3), 83-87.

[22] Cannon-Bowers, J. A., Tannenbaum, S., Salas, E., & Volpe, C. (1995). Defining competencies and establishing team training requirements. In R. Guzzo & E. Salas (Eds.), *Team effectiveness and decision making in organizations*. San Francisco, CA: Jossey Bass.

[23] Stout, R. J., Salas, E. & Carson, R. (1994). Individual task proficiency and team process behavior: What's important for team functioning? *Military Psychology, 6*(3), 177-192.

[24] Cannon-Bowers J. A. & Salas, E. (1997) Teamwork competencies: The interaction of team member knowledge, skills, and attitudes. In H. F. O'Neil Jr. (Ed), *Workforce readiness: Competencies and assessment.* (pp. 151-174). Mahwah, NJ, US: Lawrence Erlbaum Associates, Inc.

[25] Paris, C. R., Salas, E. & Cannon-Bowers, J. A. (2000). Teamwork in multi-person systems: A review and analysis. *Ergonomics, 43*(8), 1052-1075.

[26] Webster, E. J. (1989). Playfulness and computers at work. *Dissertation Abstracts International, 50*(4-A), pp. 1010.

[27] Flin, R. & Martin, L. (2001). Behavioral markers for crew resource management: A review of current practice. *International Journal of Aviation Psychology, 11*(1), 95-118.

[28] Hutchins, S. G., Hocevar, S. P., & Kemple, W. G. (1999, July). Analysis of team communications in ‘human-in-the-loop’ experiments in joint command and control. In Proceedings of Command and Control Research and Technology Symposium, US Naval War College, Rhode Island, USA.

[29] Essens, P., Vogelaar, A., Mylle, J., Blendell, C., Paris, C., Halpin, S., & Baranski, J. (2005). *Military Command Team Effectiveness: Model and Instrument for Assessment and Improvement.* NATO RTO Technical Report, HFM-087.

[30] Marks, M. A., Mathieu, J. E., & Zaccaro, S. J. (2001). A temporally based framework and taxonomy of team processes. *Academy of management review, 26*(3), 356-376.

[31] Salas, E., Dickinson, T.L., Tannenbaum, S.I., & Converse, S.A. (1992). Toward and Understanding of Team Performance and Training. In R.W. Swezey and E. Salas (eds.), *Teams, Their Training and Performance.* Ablex: Norwood, NJ. pp. 3-29.

[32] Breton, R., Ballas, J., Barès, M., Bossé, E., Foisseau, J., Jacquart, R., Jenssen, A., Kapinus, R., & Keus, H. (2004). *Modelling of organisations and decision architectures*. Final report of NATO RTO/IST-019/TG006.

[33] Espinosa, J. A., Lerch, F. J., & Kraut, R. E. (2004). Explicit versus implicit coordination mechanisms and task dependencies: One size does not fit all. In E. Salas & S. Fiore (Eds.), *Team Cognition: Understanding the Factors that Drive Process and Performance* (107-129). American Psychological Association: Washington, DC.

[34] Cannon-Bowers, J. A., Salas, E. & Converse, S. (1993). Shared mental models in expert team decision making. In J. N. Castellan Jr. (Ed). *Individual and group decision making: Current issues.* (pp. 221-246). Hillsdale, NJ, England: Lawrence Erlbaum Associates, Inc.

[35] Bowers, C. A., Jentsch, F., Salas, E. & Braun, C. C. (1998). Analyzing communication sequences for team training needs assessment. *Human Factors, 40*(4), 672-679.

[36] Williges, R. C., Johnston, W. A. & Briggs, G. E. (1996). Role of verbal communication in teamwork. *Journal of Applied Psychology, 50*(6), 473-478.

[37] MacMillan, J., Entin, E. E., & Serfaty, D. (2004). Communication overhead: The hidden cost of team cognition. In E. Salas & S. M. Fiore (Eds.), *Team cognition: Process and performance at the inter and intra-individual level*. Washington, DC: APA Press.

[38] Bowers, C. A., Braun, C. C. & Morgan, J. B. B. (1997). Team workload: Its meaning and measurement. In M. T. Brannick, E. Salas & C. Prince (Eds.), *Team performance assessment and measurement: Theory, methods, and applications*. Mahwah, NJ: Lawrence Erlbaum Associates Publishers.

[39] Casili, J. G., & Wierwille, W. W. (1983). A comparison of rate scale, secondary task, physiological and primary task workload estimation techniques in a simulated flight task emphasing communication load, *Human Factors, 25*(6), 623-641.

[40] Kidd (1961). A comparison of one-, two-, and three-man units under various conditions of work load. *Journal of Applied Psychology, 45*(3), 195-200.

[41] Urban, J. M., Weaver, J. L., Bowers, C. A., & Rhodenizer, L. (1996). Effects of workload and structure on team processes and performance: Implications for complex team decision making. *Human Factors, 38*(2), 300-310.

[42] Urban, J. M., Bowers, C. A., Monday, S. D., & Morgan Jr., B. B. (1995). Workload, team structure and communication in team performance. *Military Psychology, 7*(2), 123-139.

[43] Marks, M. A., Zaccaro, S. J. & Mathieu, J. E. (2000). Performance implications of leader briefings and team-interaction training for team adaptation to novel environments. *Journal of Applied Psychology, 85*(6), 971-986.

[44] Bavelas, 1948 A mathematical model for group structures. Applied Anthropology. Vol 7(3),1948, 16-30.

[45] Mullins, L. J., (1999). The nature of organisations. In L. J. Mullins (Ed), *Management and Organisational Behaviour* (5th ed.), Financial Times Management, London.

[46] Baron R. A. & Greenberg J. (1990). Behavior in organizations: Understanding and managing the human side of work (3rd ed.). *Needham Heights*, MA: Allyn & Bacon.

[47] Shaw (1976). Response-contingent payoffs and cooperative behavior in the Prisoner's Dilemma game. *Journal of Personality and Social Psychology, 34*(5), 1024-1033.

[48] Dekker, A.H. (2006). Measuring the agility of networked military forces. *Journal of Battlefield Technology, 9*(1), 19-24.

[49] Hollenbeck, J. R. (2000). A structural approach to external and internal person–team fit. *Applied Psychology: An International Review, 49*(3), 534-549.

[50] Price, J., Miller, D., Entin, E., & Rubineau, B. (2001). Collaborative planning and coordinated team performance. *Paper presented at the 6th International Command and Control Research and Technology Symposium,* Anapolis, MD.

[51] Diedrich, F. J., Hocevar, S. P., Entin, E. E., Hutchins, S. G., Kemple, W. G., & Kleinman, D. L. (2002). *Adaptative architectures for command and control: Toward an empiricalevaluation of organizational congruence and adaptation.* Paper presented at the Command and Control Research and Technology Symposium, Monterrey, CA.

[52] Moon, H., Hollenbeck, J. R., Humphrey, S. E., Ilgen, D. R., West, B., Ellis, A. P. J., & Porter, C. O. L. H. (2004). Asymmetric Adaptability: Dynamic Team Structures as One-Way Streets. *Academy of Management Journal, 47*(5), 681-695.

[53] Freeman, J.T, Pharmer, J.A., Lorenzen, C., Santoro, T.P., & Kieras, D. (2002). Complementary methods of modeling team performance. *Proceedings of the 2002 Command and Control Research and Technology Symposium,* Monterey, CA.

[54] MacMillan, J., Paley, M.J., Levchuk, Y.N., Entin, E.E., Serfaty, D., & Freeman, J.T. (2002). Designing the Best Team for the Task: Optimal Organizational Structures for Military Missions. In M. McNeese, E. Salas, and M. Endsley (eds), *New Trends in Cooperative Activities: System Dynamics in Complex Settings.* San Diego, CA: Human Factors and Ergonomics Society Press.

[55] Levchuk, G. M., Chopra, K., Levchuk, Y., & Paley, M. (2005). Model-based organization manning, strategy, and structure design via Team Optimal Design (TOD) methodology. *Proceedings of the 10th International Command and Control Research and Technology Symposium,* McLean, VA.

[56] Kieras, D.E., & Santoro, T.P. (2004). Computational GOMS Modeling of a Complex Team Task: Lessons Learned. In *Proceedings of CHI 2004: Human Factors in Computing Systems.* New York: ACM, Inc.

[57] Pitt, M. A., Kim, W., & Myung, I. J. (2003). Flexibility vs generalizability in model selection. *Psychonomic Bulletin & Review, 10,* 29-44.

[58] Brehmer, B. (2004). Some reflections on microworld research. In S. G. Schiflett, L. R.Elliott, E. Salas, & M. D. Coovert (Eds.), *Scaled worlds: Development, validationand applications* (pp. 22-36). Aldershot, England: Ashgate.

[59] Granlund, R. (1998). The C^{3}FIRE microworld. In Y. Waern (Ed.). *Co-operative process management* (pp. 91-101). London: Taylor & Francis.

[60] Granlund, R. (2003). Monitoring experiences from command and control research with the C3Fire. *Cognition, Technology and Work*, *5*, 183-190.

[61] Annett, J., Duncan, K.D., Stammers, R.B., & Gray, M.J. (1971). *Task Analysis.* Department of Employment Training Information Paper 6. HMSO, London.

[62] Crystal, A., & Ellington, B. (2004). Task analysis and human-computer interaction: approaches, techniques and levels of analysis. *Proceedings of the Tenth Americas Conference on Information Systems*, New York. 1-9.

[63] Shepherd, A. (2001). *Hierarchical Task Analysis.* Taylor & Francis, London.

[64] Stanton, N.A. (2006). Hierarchical task analysis: Developments, applications, and extensions. *Applied Ergonomics, 37,* 55–79.

[65] MacMillan, J., Diedrich, F. J., Entin, E. E., & Serfaty, D. (2005). How well did it work? Measuring organizational performance in simulation environments. In W. B. Rouse and K. R. Boff (Eds.), *Organizational Simulation* (pp. 253-272). New Jersey: John Wiley.

[66] Devine, D. J. (2002). A Review and Integration of Classification Systems Relevant to Teams in Organizations. *Group Dynamics: Theory, Research, and Practice, 6,* 291–310.

[67] Hart, S.G., & Staveland, L.E. (1988). Development of the NASA-TLX (Task Load Index): Results of the experimental and theoretical research. In P.A. Hancock and N. Meshkati (Eds), *Human Mental Workload*, North Holland, Amsterdam, pp. 139–183.

[68] Crowston, K. (1997). A coordination theory approach to organizational process design. *Organization Science, 8,* 157-175.

[69] Stammers, R. B., & Hallam, J. (1985). Task allocation and the balancing of task demands in the multi-man-machine system: Some case studies. *Applied Ergonomics, 16,* 251-257.

[70] Jobidon, M.-E., Breton, R., Rousseau, R., & Tremblay, S. (2006). Team response to workload transition: The role of team structure. *Proceedings of the 50th Annual Meeting of the Human Factors and Ergonomics Society,* San Francisco, CA.

[71] Hollenbeck, J.R., Ilgen, D.R., Sheppard, L., Ellis, A., Moon, H., & West, B. (1999). Person-Team Fit: A Structural Approach. *Proceedings of the 1999 Command and Control Research and Technology Symposium.* Newport, RI.

[72] Edmonds, B. (2005). Simulation and Complexity - how they can relate. In Feldmann, V. and Mühlfeld, K. (eds.) *Virtual Worlds of Precision - computer-based simulations in the sciences and social sciences* (pp. 5-32). Lit Verlag.

[73] Annett, J. (2003). Hierarchical Task Analysis. In Lawrence Erlbaum Associates (Eds.), *Handbook of Cognitive Task Design* (pp. 17-35). London: Hollnagel.

[74] Shepherd, A. (1995). Task analysis as a framework for examining HCI tasks. In A. Monk and N. Gilbert (Eds), *Perspectives on HCI: Diverse Approaches (pp. 145–174).* Academic Press: London.

[75] Dix, A., Finlay, J., Abowd, G., & Beale R. (1998). *Human Computer Interaction (Second edition).* Prentice Hall.

[76] van Welie, M. & van der Veer, G.C. (2003). Groupware task analysis. In E. Hollnagel (Ed.) *Handbook of Cognitive Task Design (447-476),* Lawrence Erlbaum Associates, New Jersey, USA.

[77] Puerta Melguizo, M.C., Chisalita, C., & van der Veer, G.C. (2006). Groupware Task Analysis and Distributed Cognition: Task Modeling In a Case of Multiple Users and Multiple Organizations. In R. Navarro-Prieto and J.L. Vidal (eds.), *HCI Related Papers of Interacción 2004,* 119 -135. Springer Netherlands.

[78] Cooke, N. J., & Shope, S. M. (2005). Synthetic task environments for teams. *CERTT's UAV-STE Handbook on Human Factors and Ergonomics Methods.* CLC Press.

[79] Rousseau, R., Breton, R., & Price, W. L. (2002). *The integration of human factors in the design process: a TRIAD approach.* DRDC Valcartier, TM 2001 – 002.

[80] Rousseau, R., & Price, W. L. (1995). Process, Tasks, and Technology. The International Federation of Operational Research Societies. *Special conference in digital technologies/multimedia: OR/MS and strategies, operations and decision support.* Santa Monica, CA.

[81] Gray, W. D., & Altmann, E. M. (2001). Cognitive modeling and human-computer interaction. In W. Karwowski (Ed.), *International encyclopedia of ergonomics and human factors* (Vol 1, pp. 387-391). New York: Taylor & Francis, Ltd.

[82] Hollnagel, E. (2004). *Barriers and accident prevention.* Ashgate Publishing Limited.

[83] Hollnagel, E., Goteman, Ö. (2004). *The functional resonance accident model.* University of Linköping.

[84] Woltjet, R., Smith, K., & Hollnagel, E. (2007). Constraint recognition, modeling and vizualization in network-based command and control. *11th ICCRTS, Coalition Command and Control in Networked era.* Paper I-152.

[85] Levchuk, G.M., Kleinman, D.L., Ruan, S., & Pattipati, K.R. (2003). Congruence of human organizations and missions: Theory versus data. *Proceedings of the 8th International Command and Control Research and Technology Symposium*, Washington, DC.

[86] Breton, R., & Rousseau, R. (2007). The analysis of team decision making architectures. In M.J. Cook, J.M. Noyes, & Y. Masakowski (Eds.), *Decision making in complex systems*. Aldershot, England: Ashgate.

[87] Hocevar, S.P., Kemple, W.G., Kleinman, D., & Porter, G. (1999). Assessments of simulated performance of alternative architectures for command and control: The role of coordination. *Proceedings of the 1999 Command and Control Research and Technology Symposium.* Newport, RI.

[88] Levchuk, Y.N., Pattipati, K.R. & Kleinman, D.L. (1999). Analytic model driven organizational design and experimentation in adaptive command and control. *Systems Engineering, 2*, 1999.

[89] Dodson, C.S., Prinzmetal, W., & Shimamura, A.P. (1998). Using Excel to estimate parameters from observed data: An example from source memory data. *Behavior research methods, instruments & computers, 30*, 517-526.

[90] Shanahan, P. (2001). *Mapping team performance shaping factors.* QinetiQ, Fort Halstead.

[91] Garstka, J. & Alberts, D. (2004). *Network Centric Operations Conceptual Framework Version 2.0.* U.S. Office of Force Transformation and Office of the Assistant Secretary of Defense for Networks and Information Integration.

[92] Jobidon, M-E., Tremblay, S., Lafond, D., & Breton, R. (2006). The role of cognition in team functioning: A matter of information sharing and coordination among team members. Chapter 3 in N. Payette & B. Hardy-Vallée (Eds), *Proceedings of Cognitio 2006. Beyond the Brain: Embodied, Situated and Distributed Cognition* (pp. 22-32). UQÀM.

[93] Porter, C. O. L. H., Hollenbeck, J. R., Ilgen, D. R., Ellis, A. P. J., West, B. J., & Moon, H. (2003). Backing up behaviours in teams: The role of personality and legitimacy of need. *Journal of Applied Psychology, 88,* 391-403.

[94] Adelman, L., Miller S. L., Henderson D. & Schoelles M. (2003). Using Brunswikian theory and a longitudinal design to study how hierarchical teams adapt to increasing levels of time pressure. *Acta Psychologica, 112*(2), 181-206.

[95] Navarro, D.J., & Lee, M.D. (2004). Common and distinctive features in stimulus representation: A modified version of the contrast model. *Psychonomic Bulletin & Review, 11*, 961–974.

[96] Stanton, N. A., Baber, C., & Harris, D. (2008) *Modelling command and control: Event analysis of systemic teamwork*, Aldershot UK: Ashgate.

[97] Sawaragi, T., Horiguchil, Y., & Hinal, A. (2006). Safety analysis of systemic accidents triggered by performance deviation. *SICE-ICASE International Joint Conference*, Bexco, Busan, Korea.

List of acronyms

C2	Command and Control
COT	Computational Organization Theory
CSCW	Computer Supported Collaborative Work
DAI	Distributed Artificial Intelligence
DDD	Distributed Dynamic Decision making
DND	Department of National Defence
DRDC	Defence Research & Development Canada
DRDKIM	Director Research and Development Knowledge and Information Management
EAST	Event Analysis of Systemic Teamwork
FF	Fire Fighter
FRAM	Functional Resonance Accident Model
GLEAN	GOMS Language Evaluation and Analysis Tool
GOMS	Goals, Operators, Methods, Selection rules
GTA	Groupware Task Analysis
HCI	Human Computer Interaction
HTA	Hierarchical Task Analysis
IPME	Integrated Performance Modeling Environment
MAS	MultiAgent Systems
OODA	Observe-Orient-Decide-Act
R&D	Research & Development
SA	Situation Awareness
SME	Subject-Matter Expert
TOD	Team Optimal Design
WT	Water Tanker

This page intentionally left blank.

DOCUMENT CONTROL DATA

(Security classification of title, body of abstract and indexing annotation must be entered when the overall document is classified)

1. ORIGINATOR (The name and address of the organization preparing the document. Organizations for whom the document was prepared, e.g. Centre sponsoring a contractor's report, or tasking agency, are entered in section 8.) Defence R&D Canada – Valcartier 2459 Pie-XI Blvd North Quebec (Quebec) G3J 1X5 Canada	2. SECURITY CLASSIFICATION (Overall security classification of the document including special warning terms if applicable.) UNCLASSIFIED

3. TITLE (The complete document title as indicated on the title page. Its classification should be indicated by the appropriate abbreviation (S, C or U) in parentheses after the title.)

Developing a framework for estimating the costs/benefits of teamwork in C2 (U)

4. AUTHORS (last name, followed by initials – ranks, titles, etc. not to be used)

Breton, R.; Lafond, D.; Tremblay, S.; Rousseau, R.

5. DATE OF PUBLICATION (Month and year of publication of document.) September 2011	6a. NO. OF PAGES (Total containing information, including Annexes, Appendices, etc.) 105	6b. NO. OF REFS (Total cited in document.) 97

7. DESCRIPTIVE NOTES (The category of the document, e.g. technical report, technical note or memorandum. If appropriate, enter the type of report, e.g. interim, progress, summary, annual or final. Give the inclusive dates when a specific reporting period is covered.)

Technical Report

8. SPONSORING ACTIVITY (The name of the department project office or laboratory sponsoring the research and development – include address.)

Defence R&D Canada – Valcartier
2459 Pie-XI Blvd North
Quebec (Quebec)
G3J 1X5 Canada

9a. PROJECT OR GRANT NO. (If appropriate, the applicable research and development project or grant number under which the document was written. Please specify whether project or grant.) 16ki06	9b. CONTRACT NO. (If appropriate, the applicable number under which the document was written.) W7701-6-2709
10a. ORIGINATOR'S DOCUMENT NUMBER (The official document number by which the document is identified by the originating activity. This number must be unique to this document.) DRDC Valcartier TR 2010-225	10b. OTHER DOCUMENT NO(s). (Any other numbers which may be assigned this document either by the originator or by the sponsor.)

11. DOCUMENT AVAILABILITY (Any limitations on further dissemination of the document, other than those imposed by security classification.)

Unlimited

12. DOCUMENT ANNOUNCEMENT (Any limitation to the bibliographic announcement of this document. This will normally correspond to the Document Availability (11). However, where further distribution (beyond the audience specified in (11) is possible, a wider announcement audience may be selected.))

Unlimited

13. ABSTRACT (A brief and factual summary of the document. It may also appear elsewhere in the body of the document itself. It is highly desirable that the abstract of classified documents be unclassified. Each paragraph of the abstract shall begin with an indication of the security classification of the information in the paragraph (unless the document itself is unclassified) represented as (S), (C), (R), or (U). It is not necessary to include here abstracts in both official languages unless the text is bilingual.)

(U) This document presents a modeling framework for estimating the cost and benefits of various team structures in Command and Control (C2). The proposed strategy combines task analysis and data-driven modeling as a means to deal with effective team design in military C2. A hierarchical task analysis (HTA) identified the set of subtasks associated with different components of a simulated C2 task. For each team structure considered, we performed a task-to-agent mapping based on the HTA results in order to identify interpersonal task dependencies and identify the activities associated with each agent (taskwork, teamwork and interaction with tools). A mathematical model is then developed to quantify the impact of each element of that mapping on individual workload. Furthermore, the model specifies the effects of workload on team performance as a function of interpersonal dependencies. The calibration of the model is based on an empirical study that tests two team structures. We then describe a tool based on this model and test its potential to estimate the effectiveness of other team structures in order to identify the optimal team design for the simulated C2 task. Finally, future work for expanding this team design tool to different C2 domains is discussed.

(U) Ce document présente un cadre théorique de modélisation permettant l’estimation des coûts et bénéfices de différentes structures d’équipe en Commandement et Contrôle (C2). La stratégie utilisée combine une analyse de tâche à une modélisation basée sur les données afin d’influencer le développement et la formation d’équipes pour des situations de C2 militaire. Une analyse hiérarchique des tâches a contribué à l’identification d’un ensemble de sous-tâches associées aux différentes composantes d’une tâche de C2 simulée. Pour chaque structure d’équipe, une association tâche-à-agent basée sur les résultats de l’analyse hiérarchique est effectuée afin d’identifier les dépendances interpersonnelles dans l’exécution des différentes tâches et les activités pour chaque agent relié aux tâches à exécuter, au fait de faire partie d’une équipe et au fait d’interagir avec des outils. Un modèle mathématique est alors développé pour quantifier l’impact de chacun de ces éléments sur la charge de travail de chaque agent. De plus, le modèle spécifie les effets de la charge de travail sur la performance de l’équipe en fonction des dépendances interpersonnelles. L’étalonnage du modèle est basé sur une étude empirique qui mesure la performance de deux équipes adoptant des structures organisationnelles différentes. Le modèle mathématique étalonné est alors utilisé pour tester son potentiel à évaluer l’efficacité d’autres structures d’équipe afin d’identifier la structure d’équipe optimale pour l’exécution de la tâche simulée de C2. Finalement, une discussion concernant les travaux futurs nécessaires à l’expansion de cet outil de design d’équipe aux différents domaines de C2 est présentée.

14. KEYWORDS, DESCRIPTORS or IDENTIFIERS (Technically meaningful terms or short phrases that characterize a document and could be helpful in cataloguing the document. They should be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location may also be included. If possible keywords should be selected from a published thesaurus, e.g. Thesaurus of Engineering and Scientific Terms (TEST) and that thesaurus identified. If it is not possible to select indexing terms which are Unclassified, the classification of each should be indicated as with the title.)

Taskwork; Teamwork; Team Functioning Elements; Team Performance; Workload; Team Structures; Hierarchical Task Analysis; Microworld Experiment; Modelling Framework; Computational Modelling; Performance Prediction

Defence R&D Canada

Canada's Leader in Defence
and National Security
Science and Technology

R & D pour la défense Canada

Chef de file au Canada en matière
de science et de technologie pour
la défense et la sécurité nationale

DEFENCE DÉFENSE

www.drdc-rddc.gc.ca